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Systems Analysis for Water Quality Management—Survey and Abstracts

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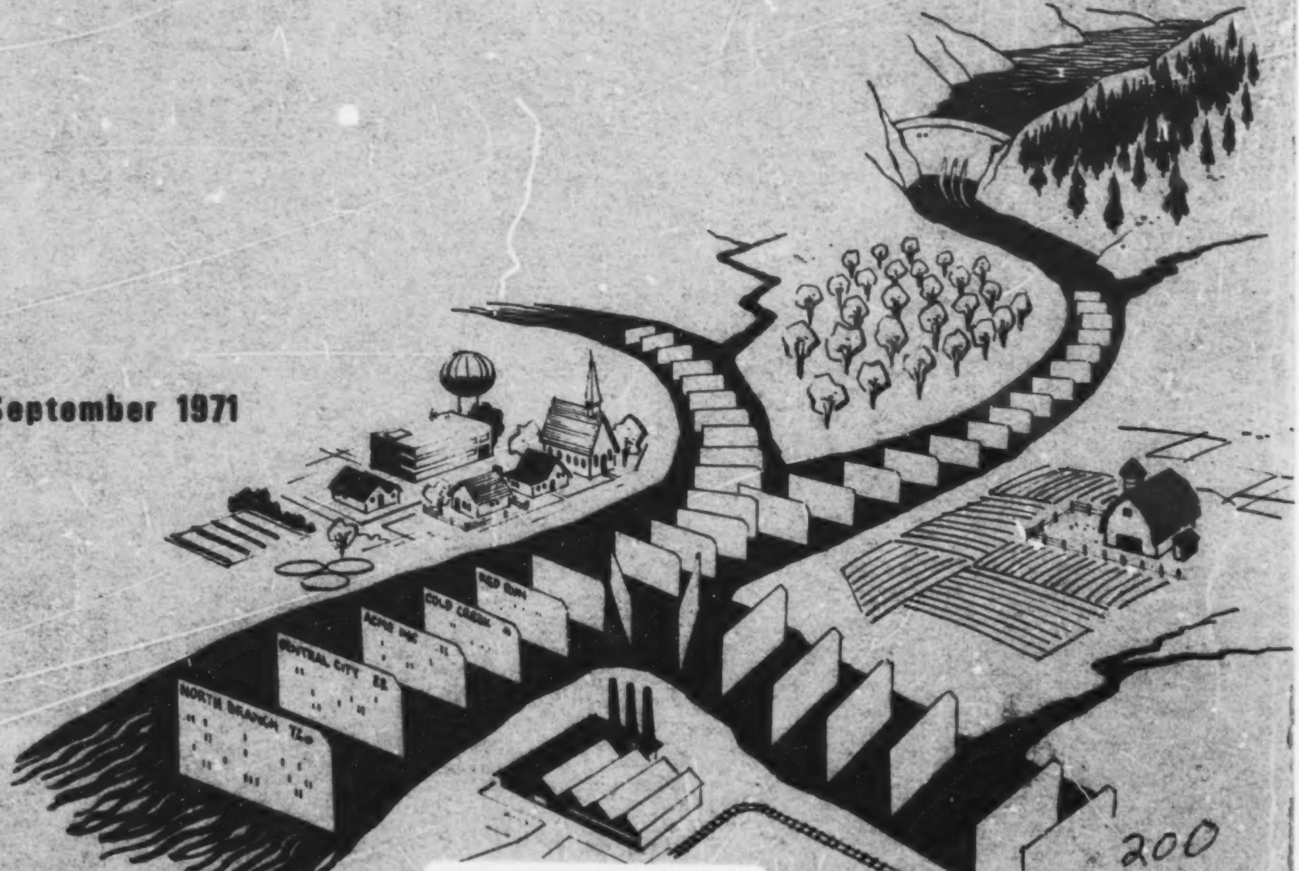
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SYSTEMS ANALYSIS FOR WATER QUALITY MANAGEMENT - SURVEY AND ABSTRACTS

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Wash., D.C. 20036

for the

WATER QUALITY OFFICE

ENVIRONMENTAL PROTECTION AGENCY

Contract #68-01-0096

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Due to the increasing scale of national efforts to clean up our streams, rivers and lakes, a survey of the current state-of-the-art in systems analysis for water quality management has been conducted. The survey is geared primarily towards helping to acquaint non-specialists with the prevailing methods, capabilities, and limitations of the analytical approach, in light of continuous rapid growth of systems analysis techniques in water quality management; physical, chemical and biological considerations in water quality modeling; and legal, social demographic, and economic aspects of water quality. Part II presents a group of relatively detailed abstracts of a representative sampling of papers in relevant analytical input areas and in the major water quality modeling areas. It is concluded that systems analysis should be simply a practical, rational and quantitative approach to illuminating, but not necessarily solving, decision issues that involve costs and benefits. (Bell-Cornell)

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ABSTRACT

A survey of the current state-of-the-art in systems analysis for water quality management has been conducted. The survey is divided into two parts. Part I gives an introductory guide to the relevant analytical considerations and techniques together with assessments of the capabilities and limitations of available systems analysis approaches. Part II gives relatively detailed abstracts of a representative sampling of papers in relevant analytical input areas and in the major water quality modeling areas. The abstracts give both technical content of the papers and critical assessments.

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PART I - SURVEY

SECTION I

INTRODUCTION

The increasing scale of national efforts to improve the quality of our streams, rivers and lakes has brought with it a demand for efficient and rational planning, management and operation of the resources being devoted to these efforts. This demand has led naturally to a growing interest in the application of systems analysis methods to water quality problems. Because of the rapid growth of systems analysis techniques applicable to the water quality area, it has become difficult for non-specialists to acquaint themselves with current methods, capabilities and limitations of the analytical approach.

This survey is intended to assist potential users and practitioners of systems analysis in understanding the current state-of-the-art without extensive literature search efforts on their part. In addition, this survey should provide an introduction to the voluminous and growing literature available for those who wish to pursue certain aspects in greater depth.

The survey itself is addressed to the non-specialist with only a basic background in water quality and systems analysis concepts. It has been structured to emphasize the pragmatic aspects of applying systems analysis to "real-world" water quality problems. This emphasis dictates the need for a balanced view of the usefulness of the various analytical approaches; as a result, at least as much weight has been placed on the limitations of systems analysis as on its possibilities.

For the reader who wishes to skim this survey as well as for the reader who intends to pursue the issue in depth, it is recommended that at least a sampling of the abstracts provided in Part II be **perused.** These abstracts have been carefully structured to provide considerable insight into fundamental assumptions as well as results achieved and not achieved in the studies reviewed.

To assist the reader, Part I has reference numbers (indexed to the Section VII reference list) at appropriate places in the text; where these numbers are followed by an asterisk, the reference indicated has been abstracted in Part II. Part II is not, however, limited to only these asterisked references; it has additional abstracts of papers and computer programs of interest to potential users and practitioners of systems analysis for water quality planning, management or operations.

SECTION II

PROCEDURES FOR CONDUCTING A SYSTEMS ANALYSIS

Systems analysis, contrary to widespread belief, is neither a separate and specialized discipline nor an arcane art. Instead, it is, or should be, simply a practical, rational and quantitative approach to illuminating, but not necessarily solving, decision issues that involve costs and benefits.

The approach as applied to specific water quality management problems can be briefly described in terms of the following steps:

1. Understand the problem - the major difficulty in accomplishing the first step is that it requires the analyst to suspend judgement in all the areas in which he invariably has prior biases: key variables, dominant relationships, appropriate modeling techniques, feasible alternatives. Much of this prior bias normally stems from the body of professional literature in any given problem area and can be attributed to the strong tendency of academic publications to redefine real-world issues in terms that permit clean and elegant solutions. It is, in fact, essential for the analyst to develop an understanding of all the problem aspects and the interactions that are unquantifiable, uncertain, controversial or obscure due to either technical or socio-political factors, particularly since these same factors may, and often do, dominate the "clean" factors. In water quality problems, the following is a partial listing of the unpleasant factors that must be at least assessed and understood prior to any formal analysis:

   a. Non-steady state or randomly variable discharges, flows, waste characteristics and biological processes.

   b. Multiple pollutant/nutrient interactions (synergistic or inhibitory effects).

   c. Unquantified (and possible unquantifiable) economic and ecological impacts of pollutants.

   d. Inadequate, variable and/or biased economic inputs: project/equipment costs: economic benefits, demand variations, prices, projections, etc.

   e. Inadequate physical/chemical/biological inputs: flows, velocities, mixing processes, growth/decay/reaction rates, etc.

f. Feasibility constraints due to social attitudes, institutional processes and relationships, political forces and jurisdictions, legal considerations and precedents, etc.

2. Restrict and formally define the decision-relevant aspects of the problem - the transition from a thorough understanding of the complexities and uncertanties of a real world problem to a considerably narrower and highly approximate formal representation of its decision-relevant aspects is the key step that determines ultimate success or failure of an analysis.

Unfortunately, many analyses begin with a one-sided justification of a preconceived problem definition rather than between the actual problem and its formal representation. At a minimum, this step must include consideration and assessment of the following:

1. Benefit, effectiveness or return factors included and those excluded.

2. Cost (economic or intangible) factors included and excluded.

3. Basis for quantification and specific selection of descriptive variables for those factors and/or processes that have been stated in quantitative terms, particularly where the descriptive variables have lower dimensionality than their underlying factors.

4. Means employed to reflect the impact of unquantified factors or, alternatively, the rationale for their absence.

5. Criteria for ranking better and poorer solutions (e.g., minimizing cost to implement a defined quality level or maximixing direct economic benefits minus costs; both of these are simple enough to become "optimization criteria") - note that absolute optimization is not essential to a systems analysis.

The problem-narrowing process is by no means rigorous; it involves both understanding of the relative magnitude of costs, effects and benefits as well as a good deal of subjective judgment. As a somewhat exaggerated example, assume that the problem to be addressed is the "best" means of cleaning up a single stream to a level suitable for recreational fishing, given a number of local industrial and municipal pollutant dischargers. Ideally, one would like to relate total local (or even national) benefits due to aesthetic/ recreational values and increased tourism (as a function of fish population density) to total local (or even national) cost. This is clearly impossible, given the state of economic and biological data and modeling.

Thus, the first step in narrowing the problem is to substitute for total benefits a relatively arbitrary determination of the type of fish population desired. However, the fish population itself cannot be quantitatively related to pollutant concentrations in the stream. Therefore, the next step is to substitute a set of water standards approximately suitable to the population desired in place of the actual fish population density.

Regarding the total economic cost issue, it is highly unlikely that the total projected effect on the local economy of increased treatment costs for local industries and municipal plants can be assessed. Consequently, a typical restriction of the problem would involve substituting direct discounted present value of treatment expenditures (including low-flow augmentation, in-stream aeration, treatment plants process changes, etc.) for total economic impact. Note that not only has the scope of economic consideration been sharply reduced, but the inherent multi-dimensionality of cost has been reduced dramatically (and probably arbitrarily) by combining public, private, present and future costs into one single-dimensional measure.

A final simplifying step often undertaken is to eliminate all nutrient and toxic pollutant standards from consideration and proceed with a one dimensional stream standard consisting of only a dissolved oxygen threshold. Unless oxygen demand is in fact the only pollution problem in the stream (a rare case for mixed industrial/domestic wastes) or unless the costs of all other pollutant removals are trivial compared to BOD removal, this step represents one simplification too many. That is, after demonstrating the minmum treatment cost scheme for meeting the dissolved oxygen standard, the original problem remains completely unsolved insofar as the desired fish population still cannot survive in the stream until the other pollutant levels fall below their respective standards.

3. Define the complete range of feasible, promising alternatives - a surprising amount of analysis has been expended on quality control alternatives that are in no sense feasible. Aside from technical consideration, the major constraints on feasibility of alternatives are as follows:

a. Social attitudes - strongly entrenched attitudes (which may be purely local in nature) such as aesthetic objections to wastewater reuse or conservationist objections to in-stream aeration may rule out otherwise attractive alternative solutions, depending on the problem and the area.

b. Institutional/political arrangements - alternatives that may have a good deal of economic merit, such as basin-wide control of treatment requirements and operations, are often infeasible (particularly as near term solutions) due to the existence of multiple political jurisdictions within the basin combined with the lack of precedent for establishing a regional commission with the requisite authority to allocate treatment resources.

c. Legal constraints - minimum cost treatment schemes for achieving a given dissolved oxygen standard in a stream or basin are often not implementable because they may call for no treatment or primary treatment, on certain relatively clean reaches when the federal/state standard requires a minimum of secondary treatment for all wastes. Another basin-wide minimization may find additional low-flow augmentation release a low cost solution to water quality problems but will run afoul of prior water rights.

d. Equity considerations - a recurring problem in imposing local and basin-wide treatment requirements is the issue of equity to industrial firms facing competitors in areas with less stringent requirements. Another major equity issue is the question of allocating stream assimilative capacity among a number of densely spaced discharges representing a variety of industries (each with different and partially unknown costs of pollution abatement) and municipalities.

A through appreciation of these constraints is essential to structuring sound and practical alternatives. However, it must be remembered that not all of these constraints are immutable; analyses addressing long term solutions are obligated to consider the effect of modifying such constraints where major efficiencies can be achieved.

Analysts often restrict themselves to considering only previously proposed or promulgated alternatives on the basis that technical experts should have the responsibility of formulating the relevant alternatives. In fact, it should be the responsibility of the systems analyst to ensure that the full range of feasible problem solutions is represented, including the possibility of new unconventional approaches.

4. Collect and assess the relevant input data - unfortunately this step normally is not accomplished until after the selection of modeling technique. In fact, data availability and quality should have a major impact on the type and complexity of model selected. If the hydrologic data base for the area is scant, there is little point in using sophisticated statistical techniques for dealing with flow variability. If pollution sources/loads or treatment costs are poorly measured or estimated, then it is hard to justify highly precise optimization techniques.

One of the most critical data assessments will be the evaluation of variability. First of all, it is essential to separate variability due to inexact measurements, approximate process models or deterministic time variations from variability due to inherent randomness (e.g., are fluctuations in biological treatment process rates due to random changes in influent composition, due to measurement deficiencies or due to variables excluded from the process kinetics). Secondly, the magnitude of the inherent variability will determine whether a convenient steady-state model can be used or whether a stochastic model is necessary to describe major effects. Given large random components, a relatively primitive model that accounts for fluctuations is normally better than a more exact model that ignores them. Similarly, if large deterministic transients with relatively short periods are involved, models roughly approximating transient behavior are more valuable than excellent representations of the steady-state.

The final and most obvious reason for data collection and assessment prior to model formulation is the need to determine the possibility of simplifying assumptions, e.g., linear costs, independence of variables, linear rate processes, etc.

5. Selection of modeling technique - given a thorough development of the problem formulations in terms of formal definition of key aspects, structuring of alternatives and comprehensive data collection/evaluation, the actual choice of modeling technique is both less difficult and perhaps less crucial than the literature emphasis would indicate.

The first and most important consideration in selection of a modeling technique is the extent to which it realistically incorporates the critical factors and relationships identified in the problem formulation. The criteria of ease of exact optimization and computational efficiency are, by comparison, secondary. All too often there is a strong temptation to accept serious distortions of the real problem structure in order to be able to employ the elegance and convenience of one of the classical optimizing techniques (e.g., linear programming, dynamic programming, etc.) Given the fact that the majority of water quality management problems have input data uncertainties of anywhere from 20% to well over 50%, it can be seen that insistence on exact optimization would be misplaced. Furthermore, water quality analyses are generally neither "canned" nor repetitive due to the prevalence of special local conditions and constraints; therefore, computational efficiency is not a prime consideration.

In view of these facts, the selection of modeling technique should proceed by elimination, in the following sequence:

a. Equations with closed form or direct iterative solutions (e.g., based on differential equations, calculus of variations, probabilistic formulations, etc.) - these are normally the simplest and most efficient models to optimize, through rarely applicable to highly multi-dimensional problems.

b. Standard algorithmic optimization techniques from the operations research reportoire (e.g., linear/geometric/dynamic programming, network analysis, etc.) - these techniques are well understood and convenient to use, provided they fit the problem and remain computationally feasible.

c. Deterministic or Monte Carlo simulations - these must be specially designed for the problem at hand, but have the best chance of realistically reproducing real world water quality situations and alternatives. Approximate optimums can be derived, but only using a variety of heuristic and/or empirical search techniques.

The latter tool has received relatively little emphasis in water quality management, although it has been extensively used in water resources planning.

6. Model verification, solution, sensitivity testing - unfortunately, the scientific tradition of rigorous empirical validation of models has not become an integral part of systems analysis practice. Nevertheless, it should be a prerequisite of all analytical studies in water quality that any model proposed (or at least the water quality descriptive component of the model) be compared with actual stream conditions over a range of flows and inputs in order to establish at least the degree of descriptive or predictive precision involved. Similarly, cost estimating relationships should be correlated against actual projects or equipments to produce a quantitative statement of their accuracy. These demonstrations should accompany any solution or recommendation; without them, analysis can easily create a spurious impression of exactness that can seriously mislead decision makers. A further important component of thorough analysis is a display of the sensitivity of solutions to perturbations in each of the dominant constraints or variables and each of the input variables for which precise values cannot be determined. In this respect the economic concept of shadow prices is highly useful in displaying sensitivity and imputed value of arbitrary constraints representing aesthetic values, water quality "requirements", equity considerations, etc. (one of the attractive aspects of linear programming is that these shadow prices are in integral part of the computation and can be directly incorporated in output formats).

Equally important and rarely presented is a demonstration of the relative scale of costs, benefits and/or savings involved in an "optimum" solution compared with overall economic activity in a plant, industrial sector or region (e.g., studies of minimum cost treatment schemes for a basin will quote x million dollars in savings for an optimum policy, but rarely give an idea of the total size of the region's economy or even of the affected industrial sector).

7. Iteration of steps 1 through 6 - because real world analyses are not conducted in the chronological sequence used here for expository purposes, and because real analysts do not have universal prescience, there is frequently a need to use the results of a later step to modify determinations made at an earlier step. It is important to allow time and effort in the course of an analysis for the implementation of this learning effect. Examination of data quality and content may make it necessary to restate the problem definition; sensitivity runs of the model may demonstrate the need for returning to the data gathering phase for several key variables, etc. The ultimate quality of an analysis will often be closely related to the number of such iterations.

SECTION III

MODELING TECHNIQUES IN WATER QUALITY MANAGEMENT

1. Introduction

Examination of the existing literature and the problems currently being faced in water quality management indicates that adequacy of modeling techniques is not a major obstacle to problem solution. In fact, it would appear that the state of the art in models has substantially outstripped the basic data and physical/chemical/biological/economic insight needed to make modeling and analytical solutions credible.

A preliminary categorization of problems in water quality management potentially amenable to systems analysis will serve to focus the discussion of models:

A. Planning
   a. Allocation of abatement resources and selection of efficient abatement strategies by reach, river, basin and nation.
   b. Regulation, standard - setting (stream and effluent), taxation and subsidies
B. Management and Operations
   a. Control of reservoir systems
   b. Control of discharge, treatment and withdrawals
   c. Allocation of monitoring and surveillance effort
   d. Allocation of enforcement effort
C. System Design
   a. Biological - trickling filter, activated sludge, extended aeration, etc.
   b. Physical/chemical - for BOD removal; removal of other pollutants
   c. Instream aeration

Each of these areas will be discussed in more detail below.

2. Analysis in Water Quality

The great majority of analytical efforts in water quality are directed towards the planning area. The analyses vary according to their treatment of the following aspects of water quality planning:

a. Pollutants - the vast majority of models address only the BOD/DO problem. A few deal with single pollutants of other types: suspended solids, single nutrients and salinity. Very few deal with multiple pollutants.

b. Water system: models addressing every level from single discharger stream reaches through full basin systems and national overviews have been constructed. Most address multiple reach single streams (with or without tributaries). Only a small number of ground water quality analyses have been attempted (except in the area of salt water intrusion). There are no combined surface/groundwater quality models that the authors are aware of (though combined surface/groundwater hydrological models are relatively common).

c. Abatement alternatives - these cover the range of standard methods: self-treatment and bypass piping for industrial discharges, individual and centralized treatment for multiple municipalities, instream aeration and low flow augmentation. Most analyses have not considered all these alternatives simultaneously, due to either model or data limitations.

d. Costs and benefits - most planning models deal simply with direct capital or capitalized expenditures for abatement to predetermined stream standards. Certain economic investigations deal with "multiplier effects" in local economies; this is done fairly often for agriculture/irrigation analyses but less frequently for water quality issues. Several attempts at quantifying recreational benefits of improved water quality are available.

e. Regulation alternatives - most planning analysis assumes direct treatment "requirements" (% BOD removal) applied to individual or grouped discharges. Equity constraints are limited almost exclusively to zoned discharge requirement schemes. Taxation as a method of regulation has been treated mostly on an abstract level. There has been only one major attempt to analyze a practical tax structure for an important stream system using actual data; it was forced to use restrictive simplifying assumptions due to lack of practical economic methods for predicting response of widely diverse industries to taxation.

3. Analysis of Management and Operations

Because there exists no institutional mechanism in the U.S. for real time control of stream quality (except for reservoir release operations), little analysis of the possibility of regulating discharges and withdrawals during periods of critical pollutant levels has been accomplished (even though Kneese, Kerri, and ORSANCO have recommended strongly the desirability of such control).

There is no extensive literature on optimizing reservoir operations for maximum returns from power and water sales, subject to required releases for satisfying water rights and predetermined minimum flows for maintaining quality. Unfortunately, this literature contains little or no description of the criteria for setting these low flow augmentation requirements.

Another operating area that offers excellent opportunities for analysis is the allocation of the limited effort level available in the monitoring, surveillance and enforcement areas. Unfortunately, there is no published literature in this area and little incentive to initiate analytical investigations.

4. Analysis of Systems Design

Due to the well-established technology of domestic waste treatment, there is an extensive literature on preliminary design cost minimization of the various types of biological treatment systems for BOD removal, though this literature is limited mainly to steady-state considerations. Recently, there has been increased emphasis on applications of the same methodologies and similar technology to industrial biological treatment systems. Generally, tertiary treatment is not considered in these analyses.

There is somewhat less complete coverage of physical/chemical treatment systems and very little other than R & D literature on newer methods such as electrodialysis, reverse osmosis and incineration. The emphasis in this literature is mostly on process feasibility and basic economics rather than on optimization, due to either the simplicity of the systems involved (e.g., direct chemical treatment) or the uncertain state of the technology (e.g., reverse osmosis).

Formal analytic models for design of systems to achieve fixed multiple pollutant effluent standards have yet to be published; such problems are currently treated on a case by case basis due to the diversity of standards and pollutant loadings for parameters other than BOD. An equally important problem is the optimization of treatment systems for the highly variable or transient loadings common in many industries. Given adequate modeling, this area could offer significant potential for cost reduction through automation and/or special supplementary treatment for peak loads (e.g., chemical treatment backup for standard biological systems).

5. Modeling Techniques - Planning

The most widely addressed problem in planning is simply that of allocating treatment effort (or regulating loads) of individual or grouped discharges on a multiple reach stream, with or without tributaries. The techniques commonly employed here are linear programming, integer programming and dynamic programming. The approach and range of problems handled by each one is discussed below:

a. Linear programming - useful general references in linear programming methodologies are Chung (1) and Gass (2). The basic linear programming formulation as presented by Deininger (3*) and Thomann and Sobel (4), consists of minimizing the sum of BOD removal costs for each discharge (using linearized cost functions) subject to the constraint that the DO deficit due to the combined effects of upstream discharges does not drop below a predetermined standard for a mesh of constraint points in each reach (additional continuity-type constraints are also imposed).

The method depends on computing linear transfer coefficients between a given discharger's load and the resulting effect on DO at each constraint point downstream. These are normally determined using the Streeter-Phelps oxygen sag equation or recent variations of the classical linear rate BOD/DO stream relationships. Since, in fact, most treatment cost curves are nonlinear, the cost functions can be included in the program as piecewise linear approximations (at the cost of a significant increase in variables and constraints) or the solution can be iterated to adjust the linear cost slopes locally; either method requires convexity of the cost function. Similar approaches have been taken by Revelle, Loucks and Lynn (5*) and Anderson and Day (6*). The method can be extended to other than unindirectional flow (e.g., estuaries) and to tributary systems.

However, realistically large numbers of dischargers and reaches can lead to impractical computer storage and time requirements unless large scale programming concepts can be introduced, that is, concepts that use more efficient specialized algorithms tailored to particular symmetrics among constraint equations often found in extremely large linear programs. An excellent review of this important area has been prepared by Geoffrion (7).

Linear programming has also been applied to optimization of multiple river - reservoir systems for maximum economic return subject to low-flow augmentation requirements and other release constraints. Parikh (8) has developed a useful decomposition of the multi-reservoir problem into individual reservoir sub-optimizations iterated for successive sets of shadow prices generated by his "master" linear program for integrating the operations of the whole set of reservoirs. The solution converges to optimal individual and multiple reservoir operating policies over a finite number of time periods with varying flows, prices, constraints, etc.

A more comprehensive treatment of regional water resources allocations maximizing total regional economic benefit including water quality flow constraints has been developed in linear programming format (again using the decomposition principle) by Heaney (9*). The model allows competition for water within the suboptimizing subregions; optimum allocation between competing regions is accomplished by iterating artifical prices for the water assigned to each subregion until the regional maximum benefit point is reached. A very large version of this program has been successfully run for agricultural activities (using total value added as the measure of economic benefit) in the complete Colorado River Basin; obtaining similar economic data inputs for optimizing industrial activities appears much more difficult.

An interesting and important application of linear programming involves the computation of effluent tax levels necessary to achieve desired stream quality levels. Johnson (10*) applies a simplified form of the Thomann and Sobel program for the Delaware Estuary to comparison of total cost under the overall minimim cost scheme, the single tax and the zoned tax schemes; unfortunately he is forced by lack of economic data to make simplifying assumptions regarding industrial response to taxation.

b. Integer programming - this technique has not found wide applicability in water quality modeling, since problems involving the linear programming format with solutions restricted to integer values for the independent variables are not common in water quality. However, Liebman (11*) has devised an ingenious application of integer programming which circumvents the sometimes serious convex cost restriction encountered in the classical linear programming formulation of minimum cost treatment allocation described above. Instead of using a continuous variable to represent BOD removal efficiency for each discharger, Liebman uses a 0-1 indicator variable to represent which one of a number of discrete treatment levels (with a separate cost associated with each) is selected by a given discharger; this allows representation in discrete form of the non-convex and even discontinuous cost functions frequently encountered (when groups of plants already emphasize certain levels of treatment). A moderate size problem using Delaware Estuary data was successfully run to compare discharge-by-discharge regional minimum cost treatment with zoned treatment requirements. It should be noted that integer programs of any size are normally computationally infeasible, with the exception of special formats such as 0-1 variables with certain constraint symmetries.

c. Dynamic programming - this technique offers both advantages and disadvantages relative to linear programming as follows:

   (1) The objective function can consist of the sum of non-linear (as opposed to only linear or convex for LP) single variable functions, as can the constraints (this is by no means a method for oprimization of generalized non-linear proglems).

   (2) For computing optimum decisions for sequenced time (or space) intervals, computing time increases only linearly with the number of decisions.

   (3) Problems with more than 2-dimensional decision variables for each stage are rarely computationally feasible.

For general references to dynamic programming techniques, Bellman and Dreyfus (13) and Neuhauser (14) are comprehensive sources. Dynamic programming has been applied for some time in period-by-period optimization of reservoir operations for maximum returns from power and water sales, where water quality is introduced only as a low flow constraint. The pioneering work in this area is Hall and Buras (15); Buras (16) gives an excellent review of the area. Erickson et alia (17*) gives a detailed specific single reservoir application involving hydroelectric, irrigation, urban and recreational benefits/losses resulting in a four decision variable dynamic program forcing the use of pattern search techniques.

Dynamic programming has been applied to the standard single stream minimum cost treatment allocation problem described under linear programming. Liebman (18) solved an eleven discharge/eleven reach representation of the Willamette River (an interesting finding is that better solution stability is obtained by solving sequentially in the downstream direction or *forward* in time, as opposed to the usual dynamic programming practice). However, as Revelle, Loucks and Lynn show (5*), the Liebman solution can be almost exactly duplicated using a far simpler linear program with only a two-piece linear approximation to the non-linear treatment cost curve. Meier and Beighter (19) extend the basic Liebman approach to allow inclusion of tributaries through a decomposition of the program into serial programs. A similar approach is taken by Joeres (20*) in treating the problem of minimum cost sediment control on a multi-branch stream/reservoir system. However, the method is still restricted to undirectional flow whereas the LP approach can treat tidal streams and estuaries (given the possibility of linearization of individual discharge effects).

d. Simulation models (Monte Carlo and deterministic) - it is to be noted that all of the above techniques are incapable of simultaneously handling stochastic flows/loads, non-linear discharge, effects and treatment costs, multiple pollutants, etc. The only technique currently available for dealing with these levels of complexity is simulation, an approach relatively unused to date in water quality studies. The technique has been extensively used in reservoir system studies since an initial Corps of Engineers experiment in 1953; Manzer and Barnett (21) give a useful description of the technique as applied in the Harvard Water Program.

Although simulation has the advantage of allowing considerably more realism in the description of the physical/economic water system, it has been avoided in water quality analysis because it requires empirical search techniques to arrive at approximate optima. In other words, the simulation can only compute points on the model's response surface (usually multidimensional) for specified input values; thus, the success or failure of simulation optimization depends on the surface search technique used. An excellent practical review of search techniques applied to multiple reservoir problems is given by Hufschmidt (22) reporting on Harvard Water Program experience. It is to be noted that complete search is rarely necessary in water quality problems where both heuristic insight and real world feasibility constraints on alternative policies can greatly reduce the size of the space to be searched. Direct simulation of randomly time-varying flows and multiple pollutant loads in a moderately complex stream system has been successfully accomplished by Pisano (12*); Moreau (79) has also developed a successful water quality stream simulator. A simplified queueing format simulation model for a reservoir/treatment plant/effluent holding tank system on a single stream reach with variable stream flows, waste flows and waste loads has been developed by Montgomery and Lynn (23*). The model treats flow in discrete increments and is thus able to handle important aspects such as treatment efficiency changes with variations in holding times generated by random fluctuations in waste flow. There appears to have been little further development based on this promising beginning.

A final and extremely important area of interest in water quality planning is the development of national assessments and national policy analysis. Very little direct water quality system analysis has been performed in this area; probably the most significant work was accomplished as part of the Wollman-Bonhem (24) model developed for the U.S. Senate Select Committee on Water Resources. Reid et alia (25*) have published their contribution to the model, i.e., the basin-by-basin projection of water quality for six pollutant characteristics and the associated tradeoff of low flow augumentation vs. effluent treatment (the application of the model in the national assessment was to compute the nation's storage requirements for low flow augmentation). The individual pollutant models are based on basin-wide loads (factored for population concentration) and on highly simplified basin-wide average decay/mixing parameters. The approximations involved are sufficiently gross that without detailed empirical validation of the resulting treatment and dilution requirements, the conclusions must be viewed as highly tentative.

There is, in fact, reason to doubt that much progress in this area can be made until a much more comprehensive data base for water use, discharge descriptions and stream pollutant levels is assembled and integrated via detailed multiple pollutant subregional models.

6. Model Techniques - Management and Operations

This area has received considerably less analytical attention than the water quality planning area.

The literature previously referred to in linear and dynamic programming for water resources is directly applicable to operations of existing reservoir/stream systems and, to a lesser extent, ground water systems. Unfortunately, the only provision for water quality in these models is normally through predetermined flows or dilution requirements for water quality purposes. There is a considerable need for additional field studies followed by modeling to relate stream quality to these dilution flows, a highly non-linear relationship due to the strong effect of stream flow levels on reaeration rates, sedimentation/scour rates plankton levels and temperature (depending on depth of reservoir releases).

In the area of regulation (particularly effluent controls), there is some overlap between analysis for planning and analysis for management or operations. On an abstract level, Kneese (26) discusses the relative merits of direct regulation of discharge contents versus effluent taxation/subsidy schemes and describes the operation of the German effluent tax system for the Ruhr. Johnson (10*) discusses in general terms the relative operating expenses (self-monitoring, surveillance and billing) of effluent regulation vs. taxation systems. He raises the important consideration of special tax rates and controls for intense transient discharges.

In this connection, Thomann (27) discusses the need for and the fundamentals of near real time control of effluent variability and treatment efficiency in the face of the substantial short and seasonal variations in streamflow normally experienced. He points out the economic and ecological inadequacies of the steady-state approach for achieving water quality goals with high probability, when hourly and daily fluctuations are taken into account. He introduces and gives examples of the important notion of stream step-response to an instantaneous pollutant input; this concept is applied to a simple feedback control of a variable efficiency treatment plant responding directly to stream conditions (and possibly to seasonal adjustments in water use/water standards). Note that this view of stream conditions requires abandoning the entire structure of steady state one-dimensional stream modeling and replacing it with transient models that include the effect of longitudinal (streamwise) diffusion. Experimental dye study techniques for addressing this problem are well-established; however, considerable measurement effort will be required to correlate diffusion behavior with channel geometry/hydrology.

Further important areas for analysis in water quality operations concern allocation of effort in enforcement and in monitoring and surveillance. In monitoring and surveillance, there is considerable need for models accounting for effort scheduling, costs, statistical strategies for sampling, continuous versus sampled measurement tradeoffs, etc. There has been almost no analytic effort in this field, though both the statistical foundations and the measurement technology are in hand. A related statistical treatment of sampling frequency requirements using a power spectral approach applied to estuarine data has been published by Gunnerson (28).

In the enforcement area, analysis would be considerably more difficult, since it would have to take into account the diversity of standards, institutional arrangements and local/state legal structure. To initiate investigations of this type, several comprehensive surveys would be needed; in particular, a detailed survey of existing standards in each state as well as a survey of the permit/monitoring/surveillance/enforcement procedures, techniques and effort levels of at least the more active states.

7. Modeling Techniques - Systems Design

The greatest obstacles to realistic optimization of treatment systems remain in the area of structuring the basic performance versus cost models of individual processes. The single process most widely modeled is the activated sludge process, almost always treated in steady state, linear kinetics fashion. Useful reviews of the basic biological treatment kinetics are given in Pearson (29*) and Eckenfelder (30) together with substantial data on the various rates, coefficients, etc. involved; results are applicable to activated sludge, trickling filters, anaerobic reactors and aerated lagoons. In these approaches, transient and instability effects are only included by means of experience limits on feasible values of loadings, detention times, etc. Direct attempts to model transient effects are reported by Smith and Eilers (31*) who present a time-varying computer model for linear kinetics of the simultaneous action of carbonaceous and nitrifying bacteria and by Andrews (32*) who presents a promising model for inhibitory, non-steady state effects in anaerobic digestion.

The literature on process models including the effects of N and P on the basic biological kinetics is scant; likewise, models for N and P removal in biological treatment are not widespread. There is, however, a growing basic data base due to strong interest in this area - see Sachs and Sheets (33) and Eliassen (92*).

In addition to a voluminous literature of models and programs for non-formally optimized complete treatment system designed based on engineering experience, there are a number of models for describing performance versus cost of multi-process treatment systems in which a wide range of process parameters can be specified, among them Smith (34*) dealing with municipal-type palnts and Parker (35*) who gives a thorough examination of treatment process alternatives for the canning industry. Both references employ basic relations based on linear, steady state kinetics. The data base for processes such as final settlers is considerably less reliable than for the widely investigated activated sludge or trickling filter processes.

There is a relatively less voluminous literature on optimization of full, multi-process treatment systems; the main techniques available are described below:

a. Surface search - naturally, any of the deterministic performance versus cost models described above (or simulation models suitable for describing more complex interactions and transients) can be approximately optimized using the same surface search techniques referred to under planning models. McBeth and Eliasson (36) report a surface exploration for minimizing cost of activated sludge processes based on grouping parameters by sensitivity. Less formal trial and error optimization based on engineering insight is common in current engineering practice.

b. Linear programming - due to the evident nonlinearity of costs and performance in treatment systems, direct linear programming applications are rare. However, techniques for iteration of linear programs to approximate non-linear (convex) costs and constraints (i.e., convex programming) have been successfully applied. An excellent example is the optimization of trickling filter design by Galler and Gotaas (37*) using a non-linear empirical performance equation and nonlinear costs. A markedly different application and approach is used by Lynn (38) in examining the problem of selecting rational planning periods over which to minimize the cost of treatment plant ownership; he gives a non-linear model of the complete stream of expenses and receipts over time and then bounds solutions from above and below with a linear programming formulation.

c. Dynamic programming - the application of dynamic programming to treatment systems that can be decomposed into unit processes connected in series is immediate and obvious, due to the serial staged nature of such systems. A straightforward example for tertiary treatment systems based on empirical unit process fits is given by Shih and Krishman (39) . A more detailed examination using standard dynamic programming format is given by Evenson, Orlob and Monser (40) and applied to the cannery treatment processes referred to above.

It is important to note that these dynamic programming formulations cannot deal with processes within a feedback (recirculation) loop; such loops must be treated as complete stages in the dynamic program. Where such a stage contains too many decision parameters to be handled computationally, the process is normally empirically suboptimized to reduce decision variables.

d. Geometric programming - a promising though not yet practically applied technique for optimizing individual non-linear processes (as opposed to full systems with processes in series) that can be described using polynomial costs and constraints is geometric programming (non-integral positive exponents for the polynomials are permissible). Meier et alia (41*) give an introduction to the technique with a simple tank/pump system example.

e. Pontryagin maximum principle - this standard optimization technique in control theory has been applied to rather abstract system design problems with relatively artificial cost functions. It represents in essence a generalization of classical calculus of variations. Erickson, Yo and Fan (41*) applied a discrete version of the maximization principle to optimum allocation of loads between stages of completely mixed and plug flow step aeration systems. Unfortunately, the optimization criterion is minimum volume which is by no means equivalent to minimum cost; nevertheless, the results yield interesting insights into the marginal benefits of extra stages and the comparison of completely mixed with plug flow processes. Tarassov et alia (42) , solving for optimum river reaeration policies, apply the maximization principle to a system of partial differential equations describing DO as a function of artificial reaeration effort distributed quasi-continuously down a stream reach. Again, the optimization criterion is relatively artificial: it is the streamwise integral of squared DO deficits weighted by an arbitrary cost plus the integral of the square of the DO artifically added.

SECTION IV

PHYSICAL, CHEMICAL AND BIOLOGICAL CONSIDERATIONS IN WATER-QUALITY MODELLING

1. Introduction: The Complexity of the Problem

Models, however complex and sophisticated they may be, are simplifications and approximations of natural phenomena. When the natural phenomena are well understood, carefully measured, and confirmed by years of accurate observation, a model may have excellent descriptive and predictive power. However, when the underlying phenomena are thoroughly understood, described and confirmed, any model based on them must be used with caution, intellectual humility, and some appreciation for its relative strengths and weaknesses. In this chapter we shall discuss some of the most important physical, chemical and biological matters that must be borne in mind in evaluating a water-quality model. The most important lesson is that water-quality phenomena are complex, dynamic, and interrelated; the chemical, physical, and biological aspects of water-quality are alloyed in reality. When this alloy is decomposed and simplified for analytical convenience in modeling, one must take care not to confuse the analytical solution with the often insoluble complexities of real water-quality problems.

An example or two may help. Many water-quality phenomena are closely related to mixing. Wastes are diluted by mixture with flowing water; they are chemically changed by the action of oxygen that has been dissolved in the water; they settle as sludge or are caught up in the streamflow, depending on the strength of turbulent mixing in the water. Many determinants of mixing are to be found in the streambed: its slope, contours, geometry, roughness, twists and turns. In sections of a stream where the bed slopes gently, where the contours and geometry of the cross-section change frequently, where the bed is rough, and the channel twists and turns every few yards, mixing will be excellent, wastes will be quickly dispersed and thus offer themselves more readily for cleansing by a variety of physical, chemical and biological processes. Where the bed is deep, straight, smooth and invariant, there will be much less mixing and much less opportunity for chemical, physical and biological purification. Many water-quality models pay no direct attention to the streambed; they deal instead with certain derived attributes generally treated from a steady state pont of view (such as mean flow, reaeration coefficients, mean velocity, mean depth). These attributes are analytically convenient but less informative and often downright misleading, because the variations in depth, flow, etc., are usually much more significant than the corresponding averages. Perhaps the most telling example is average concentration of toxic matter: it is not necessarily the long term average concentration of a poison that converts a river into a biological disaster; rather, it may be the maximum concentration over a few minutes or hours that determines whether the organisms that depend on the river will live or die. One lethal dose kills, even if the river is free of poison for the next six months and even if the six-month average is innocuous.

The system analyst who must deal with water-quality models is advised to spend some time in familiarizing himself with (1) the body of water that is being modelled and (2) the most important fundamental concepts in physics, chemistry, and biology of water-quality research. Maps, charts, and other decriptive materials -- often excellent -- are available from a variety of sources: state agencies (such as departments of natural resources, water boards, pollution-control agencies, engineering advisory offices, etc.), interstate and regional agencies (such as interstate compact commissions and regional interstate river-basin commissions), and a wide variety of Federal agencies (including the Geological Survey, and the Coast Guard, the Army Corps of Engineers, the Bureau of Reclamation, the Soil Conservation Service, the Fish and Wildlife Service, and the Bureau of Outdoor Recreation). Several excellent introductory treatments of water quality are generally available; Kittrell's superb handbook (43) and the "Green Book", Water Quality Criteria (44) are especially recommended.

2. Basic Considerations and Terms

There are two principal types of water-quality models: (1) those that model water quality due to a single discharge, such as the outlet of a sewage-treatment plant, and (2) models of related points. The second type of model is usually more complex because it must deal with water quality as multiple functions of distance and/or time of travel in the flow. Roughly speaking, the first type of model is Eulerian, the second Lagarangian. For expository convenience, we shall concern ourselves mostly with the latter because they include the full scope of physical, chemical, and biological phenomena that pertain to water quality.

Models of water quality must begin with waste sources. There are two general types: (1) point sources, usually limited to municipal and industrial wastes, and (2) area sources, principally agricultural wastes. Very little has been done to model area sources, although agricultural pollutants (such as pesticides, herbicides, fertilizers, salts leached from soils by extensive irrigation, and microbial nutrients leached from manure piles in animal feedlots) have begun to receive a great deal of attention. In fact, area sources are all too often ignored in studies of optimum allocation of treatment resources. Although some industrial wastes are included in municipal wastes, municipal wastes generally are of two related types: (1) so-called sanitary wastes, and (2) miscellaneous wastes such as garbage that enters the sewer system through such routes as garbage disposal units. Both types of municipal wastes are predominantly organic materials of biological origin, largely food, its digestive end-products, food scraps, and street litter.

Industrial wastes are not so easily categorized: Each industry produces wastes that are characteristic of the manufacturing processes it employs. The wastes from a petroleum refinery are vastly different from those of a sugar-refining plant, a paper factory, a thermal-electric power plant, a mineral-processing plant, a soap factory, or an industrial chemical plant. The types of pollution problems that these wastes create are similarly diverse, ranging from thermal pollution (hot -- or more usually simply warm -- water, which can damage aquatic life and disrupt the chemistry of the stream) to weak acids that drain from abandoned mines, to tons of pulverized tailings from mineral processing plants, to a variety of offensive colors, odors, and toxic chemicals.

The system analyst must constantly keep in mind the enormous diversity of wastes that may be dumped into water. Unfortunately, due in part to traditional emphases in sanitary engineering, most water quality models are concerned only with BOD or COD (biological and chemical oxygen demand), which only measure -- and not too precisely, at that -- the amount of oxygen that is required to convert organic wastes into carbon dioxide, water, and other simple oxides. Many kinds of wastes, however, exert little or no BOD or COD.

Hot water discharged from a power plant may cause a serious pollution problem, without affecting oxygenation (other than through temperature effects on oxygen saturation and on metabolic rates) in the least. Taconite tailings from an ore-dressing plant may smother a lake bottom and all the life that dwells there without contributing BOD or COD at all.

Nevertheless, most models are concerned only with one or another aspect of oxygen demand, as though water pollution were synonymous with oxygen depletion. The oxygen content of water is usually cited as DO (dissolved oxygen). When readily oxidized matter is introduced into water, microorganisms will metabolize it, thereby consuming some of the DO. A graph that depicts the lowering and recovery of DO vs. distance below a BOD discharge point is called and "oxygen-sag curve." At the same time that DO is being consumed, the water will dissolve fresh quantities of oxygen as it continues to flow; this process is called reaeration, and it is exceedingly complex. Although there is a variety of models that purport to describe the relationship between oxygen-demanding wastes, DO, and reaeration, the system analyst is warned that the relationship is in fact not very well understood at all: It is obscured by any number of unknowns, unaccounted factors, and an insufficient data base.

DO is not the only measure of water quality, and a body of water may "assimilate" many kinds of waste besides oxygen-demanding wastes. A stream may have a perfectly acceptable DO, yet be dangerously polluted. It may be loaded with pathogenic bacteria, viruses, protozoa, and parasites; it may be excessively acid or alkaline; it may be too warm, too turbid, or contain unacceptable concentrations of hazardous inorganics such as boron, cadmium, lead, or mercury; it may have dangerously high levels of agricultural pesticides and herbicides; it may simply be too saline (which is one of the principal water-quality problems of the Lower Colorado River Basin). Nevertheless, the system analyst will discover that the vast majority of models are concerned only with DO, BOD, or COD, the oxygen-sag curve, and reaeration.

Once the wastes have been introduced into the water, they become part of an extraordinarily complex and intricate reaction system whose physical, chemical, and biological parameters are dynamic and interrelated. They are mixed in three dimensions (vertically, laterally, and longitudinally); precipitated and scoured; exposed to many kinds and sources of energy (mechanical, thermal, optical, chemical, and biochemical); passed by and over a variety of filters and adsorptive sites -- ranging from clays, gravels, sand, rubble, cellulosic materials, and biological detritus to dense populations of aquatic plants and animals, whose surfaces (including the surfaces of their digestive and respiratory tracts) offer excellent reaction sites; and put into contact with all the other chemical compounds in the water.

When we speak of a stream "assimilating" wastes, we are compressing into one word all the physical, chemical, and biological processes that purify water. The chemical mechanisms alone include ion exchange, acid and alkaline hydrolysis, auto-oxidation, photolysis, catalytic oxidation, enzymatic oxidation, and a long gamut of addition and substitution reactions. As the wastes are carried along by the current of water, they are progressively exposed to these purifying processes; but the progression of processes cannot be predicted with any confidence; thus, it will be seen that most models of instream processes are largely empirical and rarely precise.

The physical factors of a stream or current are so interrelated that it is almost impossible to separate the effects that they bring about. The slope and roughness of the water course influence both depth and speed of flow, which together control turbulence. Turbulence, in turn, affects mixing rates, reaeration, sedimentation and scour, growths of biological forms attached to the bottom and sides of the channel, and rates of natural purification. Water temperature affects the rate at which wastes are decomposed, the amount of dissolved gases (especially oxygen) that the water can hold, and the forms of life that can flourish in the water. Turbidity and color affect the quantity of light that can penetrate the water's surface to sustain photosynthesis by aquatic light-dependent chemical reactions.

3. Hydrological Inputs for Analytical Modeling

For general background in hydrology, Chow (45) represents a useful reference. Specifically, an essential input (or set of test conditions) for any water quality model that accounts for flow variations over time is a streamflow record that 'realistically' represents the flow that can be expected over the planning period employed. Where historical records of sufficient length and accuracy are available, these are often used in raw form. In the more common case where such records are unavailable, synthetic flows derived from available or correlated records must be generated. The basic references for monthly streamflow generators are Beard (46) and Thomas and Fiering (47). Matalas (48) has a useful review of the methods of synthetic hydrology. Monthly (or yearly) generators are generally based on a transformation and distribution fit (usually log Pearson Type III or log normal) to the available data with serial correlation coefficient estimates for each month; normally, correlation with any month before the immediate predecessor has been found insignificant. The resulting statistical parameters are then used to transform the output of a random number generator to any desired length of record. This same basic technique is extended to correlate different gaging stations on the same or different streams when inputs for modeling of multiple reaches or streams are required. A further extension developed by Benson and Matalas (49*) allows the generation of synthetic monthly and annual flows for multiple ungaged locations in a basin; the technique developed is simply the regression of means and standard deviations for the gaged locations within the basin on six basin/climatic variables. The regression formula then predicts the statistical parameters of flow for any other location in the basin, though with considerable prediction error.

The generation of daily (or shorter period) synthetic hydrographs is considerably more difficult due to the need to preserve realistic behavior of the ascension and recession curves around peak and low flows; the behavior of these curves appears to have a strong deterministic component not accounted for by straightforward statistical methods such as Beard's second-order Markovian daily generator (46). A non-rigorous but considerably more realistic (and impressively validated) technique is presented by Payne, Newman, and Kerri (50*); the technique is based on rearrangement of the daily records around the critical event(s) in each month in order to preserve ascension/recession behavior. After rearrangement, the statistical treatment follows the standard methods described for monthly generators.

Of more specialized interest in water quality modeling is surface runoff hydrology; Betson et alia (51*) have a successful simplified empirical model for predicting runoff from rainfall data; Huggins and Monke (52*) present a theoretical model based on micro-detail.

For groundwater hydrology there exists a voluminous literature;a good basic reference is Todd (53). The area of most direct interest to the water quality analyst invlolves the fitting of a ground water model for elevations, heads, storage, etc. to the usually inadequate data available. Although least squares and linear programming techniques for fitting the requisite parameters exist, e.g., Kleinecke (54), they generally do not provide satisfactory results. Two interesting practical approaches are available: Vemuri and Karplus (55*) present a practical hybrid computation procedure based on Pontrayagin's maximization principle that allows direct application of hydrological insight and experience; Meyer (56*) develops a direct stochastic perturbation technique for sensitivity analysis of groundwater models.

4. Dissolved Oxygen Modeling

The bulk of water quality models are concerned with DO as the measure of stream pollution. DO is in fact one of the most important aspects of pollution, though it does not necessarily dominate water quality considerations in all stream situations. Due to the long history of interest in this parameter, there exists more literature on BOD/DO modeling than on any other stream pollutant. Unfortunately, this does not imply either completeness or satisfactory accuracy in current methods.

The basis of most work today remains the Streeter-Phelps equation which assumes steady state conditions and linear deoxygenation rates proportional to BOD_5 loads plus linear reoxygenation rates that are constant for a given stream reach. Various authors, Dobbins (57), O'Connor (90*), etc., added other linear rates or constants to represent benthic demands, photosynthetic contributions, sedimentation, etc.

Falk (58) has made a significant advance in realism by developing a model which accounts for two stage BOD (carbonaceous and nitrogenous) from multiple sources and varying temperature profiles (and associated saturation levels), heat loads and stream cross sections. Li (59*)has developed a variety of non-steady state solutions (retaining one-dimensional flow, however) to represent diurnal variations in load/photosynthetic contribution, cross-section and runoff input variations, etc.

An extremely useful area is the prediction of stream behavior without a need for in-stream measurements. Churchill et alia (60*) made a significant step in this direction with an excellent series of field studies on reaeration constants in clean streams, resulting in an empirical fitting equation using depth and velocity. Isaacs (61*) significantly improved the fit and the theoretical validity of the predictive model. To complete the capability of approximately predicting stream DO behavior without in-stream measurement, the following are needed:

a. A predictive characterization of the effect of general pollutant concentrations in changing reaeration rates from the basic clean water rate.

b. A predictive characterization by industry or process of both the basic deoxygenation rate and the general shape of the BOD curve for a comprehensive cross-section of important wastes.

A number of authors have conducted field studies on photosynthetic contributions and diurnal variations, including Meritt et alia (62*), Rudolfs et alia (63*) and Ignjatovic (64*). It is clear that photosynthesis is a major oxygen contributor (up to 75% of total reaeration has been reported); unfortunately, despite the successful fitting of Fourier series approximations to the diurnal cycle by Kartchner et alia (65*) it is not clear that the data base is sufficiently complete to allow prediction of amplitudes as a function of algal density, ambient light, turbidity, nutrients, etc.

Another important area is the analysis of stochastic variations in DO, due to load, streamflow and biological process variations. An interesting model has been presented by Thayer and Krutchkoff (66*) based on a probabilistic formulation of the Dobbins deterministic approach; mean DO results coincide with Dobbins but DO variability is shown to increase as DO decreases, implying that the worst fluctuations can be expected under the worst pollution conditions. Other authors have recognized the inadequacy of planning deterministically to a deterministic DO standard, notably Loucks and Lynn (67).

A final area, as yet uninvestigated for stream situations, is the modeling of large transient BOD inputs including the effect of longitudinal mixing (thus eliminating the usual one-dimensional assumption), in accordance with Thomann's concept of a stream step response (27*). Such modeling would require extensive dye studies in the field in order to be able to predict the mixing properties of a stream from its physical configuration. The importance of such studies derives from that fact that they are required in order to be able to impose needed peak effluent regulations on discharges (slug discharges are responsible for a significant portion of fish kills).

SECTION V

LEGAL, SOCIAL, DEMOGRAPHIC, ECONOMIC, AND OTHER RELATED ASPECTS OF WATER QUALITY

1. Introduction

Because water is one of the Nation's most important basic resources, a resource that is tapped by almost every human activity, systematic studies of water and water quality have inevitably grown to include almost every major activity and to incorporate every intellectual discipline. Every principal water agency of the Federal Government now conducts systematic studies of water requirements (both present and projected) that include demographic patterns and trends, economic analysis, sociological and political trends, and legal considerations, in addition to hydrology and water-quality sciences. The literature on these related factors is enormous; in this short chapter we can do little more than refer the interested reader to the most important sources, and quickly summarize the most important trends in recent studies. Some of the most important on-going research is also discussed.

Adequate supplies of water of acceptable quality are essential to the Nation's health, welfare, and prosperity. As the nation has grown, pressures on its water resources have become acute; in some regions (such as the High Plains of Texas and the Lower Colorado Basin), water is already the limiting resource for certain critical economic activities, such as agriculture. To conserve and make the wisest use of the Nation's water, comprehensive planning studies of water in relation to economic growth, environmental policy, demographic shifts, technological development, interregional and intersectoral competition, are conducted by administrative policy in all of the Federal agencies that participate in the Water Resources Council. The universities (especially those that have Water Resources Research Institutes that were established by the Water Resources Research Act), private or semi-public research institutes (such as Resources for the Future and the Brookings Institution), and lower levels of government also conduct or sponsor studies of water quality that include these related factors.

While comprehensive scope and global perspective are admirable in any truly systematic study, these same qualities can also lead to formidable practical problems such as incomplete or grossly inadequate data to support such ambitious analyses, insufficient sensitivity to interactions among factors, and uncritical extrapolations of purely fortuitous historical trends into the nebulous future. The most ambitious of these studies are virtually indistinguishable from master plans for national economic growth; those that concentrate on purely local water-quality problems often suffer because they are unduly negligent of larger regional and national issues whose resolution must necessarily affect the pattern of water use in every locality.

All systems studies of water must ultimately be framed in terms of two categories: water quantity and water quality. Every other category of analysis depends on these two, for these other categories are all concerned with allocation of the resource among competing uses and users, incidence and distribution of the associated costs and benefits, restraints on use, and provision for future use by generations yet unborn.

The definiencies of water quality studies that fail to consider the most important related factors (such as economics) are usually readily apparent and need no further comment here. The problems of global inclusiveness, however, merit some analysis. One of the most instructive examples is the Water Resources Council's plans for the Second National Assessment of the Nation's Water Resources (2d Assessment, hereinafter).

The Water Resources Planning Act of 1968 (P.L. 89-80, 42 USC 1962a et seq.) created the Water Resources Council as a forum for coordinating the activities of all the Federal water agencies. One of the Act's provisions empowers the Council to assess the Nation's water resources from time to time and to report the results to the President and the Congress. The principal objective of these assessments is to alert the Nation to its water problems (i.e. insufficient quantity, inadequate quality, and their consequences) so that preventive or corrective action can be taken. The 1st Assessment was prepared and published soon after the Council's establishment; it was hastily prepared and torn apart at leisure. The principal deficiencies of the 1st Assessment included insufficient data (especially on water quality and water use), inadequate analysis of interactions among factors (e.g. regional ambitious for water-related economic growth as opposed to balanced national economic growth or national economic efficiency), marked oversimplification of dynamic factors (such as population growth, demographic shifts, the direction and pace of technological development), and insensitive techniques (based on simple extrapolations of recent historical trends) for projecting future water requirements.

The Council began planning for its 2d Assessment almost immediately. A contract was awarded to A.D. Little, Inc., to draw up plans for the 2d Assessment; the final report for this contract was published in 1970, but not widely distributed. These plans were made public at a symposium sponsored by the U.S. National Bureau of Standards (7-8 May 1970) and criticized by an audience that included hydrologists, engineers, economists, planners, and system analysts from several prominent university facilities, the Geological Survey, the Federal Water Quality Administration, the Office of Water Resources Research, the National Water Commission, the General Accounting Office, the Economic Research Service, the Office of Business Economics, and the Corps of Engineers. Much of the following analysis is summarized from that discussion.

A.D. Little's plans were comprehensive indeed. Two layers of analysis were defined: a hydrological layer, and a superimposed economic-demographic layer. The hydrological layer called for a complete quantity-quality model of all the Nation's water, both surface water and ground water. The Nation was to be divided into approximately 20 hydrological regions (roughly corresponding to the river-basin regions of the 1st Assessment); these regions were to be subdivided into subregions, and the subregions subdivided into zones. The model was to describe and predict the quality and quantity of water as it flowed from zone to zone within subregions, and from subregion to subregion within regions; interregional transfer of water was explicitly excluded, partly for legal reasons.

Several hydrologists inquired where all the data on quality and quantity would come from. The fluctuating quality of the Nation's waters is not at all well documented: there are great gaps in the data base, and much of the available data (such as BOD measurements) are notoriously erratic. While the data on water quantity are more complete, they are not up to the zone-by-zone analysis A.D. Little calls for, particularly in the arid West, where much of the scarce water is from ground-water sources that are incompletely charted, and whose flows are not well documented. Several in the audience commented that if this large and expensive model could only guess at hydrological data for the arid West where problems of water quantity are already the most severe in the Nation, why bother with it at all?

The superimposed grid of demographic-economic data creates other problems. The purpose of constructing this second grid is to compare, analyze, and predict probable water demands in relation to the probable water supply (which the underlying hydrologic grid was to have shown). The three principle types of data in the superimposed grid are: (1) demographic data (population densities, distributions, and growth patterns); (2) agricultural data (consumptive uses of water for irrigated farming, and alterations in water quality by fertilizers, herbicides, pesticides, agricultural and feedlot wastes; and (3) industrial data (location of industries and specification of their waste effluents). These data were to be supplied by two principal Governmental sources: the Office of Business Economics (OBE) of the Department of Commerce and the Economic Research Service (ERS) of the Department of Agriculture (the initials of these two agencies were combined into one acronym, OBERS, and the OBERS system for producing joint demographic-agricultural-industrial data for water-management studies has become an important data source).

There are several difficulties in the OBERS system, and they are the familiar ones: inadequate data, controversial (many would say "mistaken") methods of analysis, and insufficient sensitivity to the dynamic factors that will shape future needs for water.

The fundamental demographic data are certainly sound enough since they are based on the U.S. Census. Projections of these data are another matter altogether. Estimates of the population growth rates have been shrinking every year for the last several years; the great population increases that the experts predicted just ten years ago have fallen far short of the mark; the experts now predict a very slow growth rate, but they could be just as wrong. There is ample reason to doubt the accuracy of the estimates. Yet our pollution-abatement activities today must be synchronized with the growing pressures for water for tomorrow. It makes a great difference in our water-quality activities to know when we must have sufficient clean water for a population of 400 million. Much depends on our knowing with some precision how many people will live in which areas at what time in the future. If people continue to congregate in a few densely populated urban areas, water quality problems will be concentrated there. If they continue to migrate heavily to the arid Southwest, the competition for water between cities, industries, and agriculture in that semi-desert region will be exacerbated.

One powerful reason that the experts guess wrong is that demography is sensitive to a variety of governmental policies that may be as fickle as election results. Population growth is very sensitive to such factors as wars, depressions, inflations, and the whole constellation of factors that encourage upward mobility. Population shifts are also sensitive to governmental policy. A combination of technological advances and federal policies on agriculture and irrigation helped accelerate the depopulation of farm communities, and contributed to the substantial shift of agriculture from the wet Southeast to the arid Southwest. The development of large industrial complexes in certain rapidly growing urban areas (such as Phoenix, Los Angeles, and Houston) has been intimately related to the award of large Government contracts. In the absence of sustained and explicit governmental policies on such matters as population growth, population distribution, regional economic growth, national economic efficiency, and similarly fundamental issues, demographic prediction is subject to large errors. The systems analyst must be distrustful of all models whose results depend in any way on long-term demographic projections.

Hydroeconomic data on agriculture are even more restricted. The dynamic factors in this area are even more dependent on govermental policies and on the predictable pace and direction of technological development. The enormous labor of sorting out the contribution of irrigated agriculture to our national production of food and fiber is just now being undertaken systematically by Prof. Earl O. Heady and his colleagues at the State University of Iowa. Until Heady's analysis is complete, one can only approximate the quantities of water that the nation must set aside for irrigated agriculture. The whole question of agriculture's needs for water is intimately bound up with such policy issues as the soil bank, price quotas and acreage restrictions, agriculture export and import restrictions, and substantial food give-away programs. Change any of these policies, and agriculture's needs for water will be affected. Shifting large segments of agriculture from the Southwest to the Southeast through changes in irrigation policy would necessarily affect water quality in both regions: agricultural pollution would increase in the Southeast and decrease in the Southwest. Removing the subsidy on sugar beets would eliminate beet sugar and its attendant pollutant loads (and as a concomitant, would create the problem of finding some use for the displaced land, labor and facilities). No model of national water-quality problems can afford to ignore these problems, but none can deal with them either, except by postulation. These circumstances create a modeller's nightmare, none-the-less, it is incontrovertible that many of the major determinants of water quality depend on policy factors that cannot be accurately defined or predicted. Although the OBERS system draws on all the accumulated experience of the U.S. Department of Agriculture, it is virtually helpless to deal with dynamic factors in agricultural water consumption.

Considerations similar to those in agriculture apply to industry's needs for water and the associated water-quality problems. A few sizeable changes in international trade agreements and in federal tax law could create or wipe out whole segments of industry. The discovery of a reliable and cheap source of new energy (such as the direct conversion of atomic energy to electrical energy) could revolutionize American industry, and utterly change industry's needs for water and its water-quality problems. Here again, the national assessment models of A.D. Little cannot begin to deal with the challenge of prediction in the face of changing policy and technology. And here, too, the available data on industry's water needs and waste-disposal problems are simply not adequate. One observer from the General Accounting Office seemed to crystallize the sense of the adverse comments when he noted that if we have to guess about future demography, about current and future agricultural economic data, about almost all aspects of water-quality problems due to cities or industries or to farming, about the movement of water from zone to zone, and so forth; if we have to guess about all this, why not just make one or two big quesses at the end about water quality and water quantity rather than spending so much time and money fabricating data to feed into an extremely expensive computer model that will do no more than produce a highly compounded guess.

Because these complex policy and technology factors must be considered but cannot be incorporated except by some axiomatic method, it is now increasingly common for modellers to run their analytical and simulation routines against a variety of policy and technology factors combined into various scenarios. Current examples of policy scenarios in water quality models include the Heady model for irrigated agriculture, the interregional and intersectoral models of the National Water Commission (R.G. Thompson) and the very influential Wollman-Bonem model for quality, quantity, and cost in 22 major water resources region The Wollman-Bonem model (24) has been widely circulated in manuscript, and has just been published. Because this model has become so well-known, it is worth devoting a few paragraphs to a summary description.

The Wollman-Bonem model emphasizes national and basin level water quality considerations; the model was constructed to evaluate three water-quality policies or strategies:

1. least flow of water to dilute wastes; waste treatment is maximized, thereby bypassing the requirement for releasing water stored in reservoirs to dilute wastes to acceptable levels of water quality.
2. least treatment of wastes; storage of water in reservoirs is maximized, thereby creating the largest volume of stored water being kept at the ready to dilute waste-filled waters. Dilution replaces waste treatment.
3. least cost; water storage and waste treatment are selected in combinations so as to minimize cost for a specified level of water quality.

Each of these policies (or strategies) is run against a range of assumptions and specifications that cover other variants such as projected withdrawal and consumptive uses, storage costs, interest rates, amortization rates, water-quality standards, and probability of minimum streamflow. Because this model was first published in 1960 and has been extensively criticized, refined and extended during the last ten years, it is one of the pioneering attempts in national water quality analysis. In the latest version of the manuscript reviewed by the authors of this report, stream quality was represented by three parameters: dissolved oxygen, phosphorus, and nitrogen; it was assumed that pollution due to microbes, chemicals, and suspended solids would be reduced to acceptable levels by the dilution flows that would be required to meet stream standards for dissolved oxygen. Although the model has been widely acclaimed, the systems analyst is warned that the Wollman-Bonem model involves major unverified approximations and is not self-contained: it requires data on water use, on the costs of regulated streamflow versus treatment, and on pollution loading. The difficulty of obtaining reliable and accurate data on any of these three is well known; the results of the model must be interpreted with the limitations on data and basin-wide approximations in mind.

The following sections represent a brief introduction to major concepts, literature and data of importance to the analysis of water quality management.

2. Legal/Social/Political Aspects Relevant to Water Quality Analysis

Water resources in the United States are subject to a bewildering variety of governmental controls and jurisdictions due to the diversity of interests and political geographies involved. The tradition of public control of water predates the American legal system by many centuries; it is universally recognized that water resources cannot be managed through the normal operations of a competitive market and private property system.

The fundamental body of law controlling water resources is concerned with the right to use of water. Water rights law is divided into two general doctrines, the riparian rights concept which holds in the East and the appropriative rights concept which applies throughout the West.

The former operates under the principle that every owner of property adjoining a water body has a right to have the flow continue undiminished in quantity or quality, a condition that is clearly impossible to guarantee literally. In practice, this principle allows the riparian owner to sue upstream dischargers or withdrawers for any damage that he can demonstrate he has sustained. Such suits have not, in general, been effective in preserving the quality of Eastern streams due to the difficulty of proving substantial damages.

The western appropriative rights doctrine holds that surface waters may be appropriated for beneficial use by any person, subject only to non-interference with previously established appropriative rights (these rights fall under state rather than federal sovereignty). This system also has substantial drawbacks, particularly with respect to overall social/economic benefits, not to mention the inequities that can be created through purchase of land with its associated water right by powerful economic interests (e.g., the famous Owens Valley War in which Los Angeles purchased and diverted enough water rights in the Owens Valley to wreck the Valley's economy and land values). An excellent review of water rights law is contained in Hutchins (68).

It is to be noted that the status of percolating groundwater is considerably different. By and large percolating groundwater has legal status similar to underground mineral resources; with the exception of certain states such as New Mexico, groundwater is privately owned as a direct concomitant of land ownership. Where well defined underground channels exist, the surface water rights doctrines can be (but are not always) applied. Needless to say, these legal distinctions cannot be sustained hydrologically; thus, there is an increasing trend toward local (and possibly national) regulation of groundwater use and quality, through special groundwater districts, powers of taxation, permit systems,

Useful references concerning existing legal arrangements specifically related to water quality and their variations across the country are Wollman (69) and Sax (70), (71). Due to the rapid development of legal precedents in this area, periodicals such as the Bulletins of the Environmental Law Institute and the Environmental Reporter may be important to the analyst concerned with constructing legally feasible alternatives for water quality management in various areas.

The local variations in applicable law correspond to the great variety of interlocking and overlapping political mechanisms and jurisdictions controlling water, from township and special purpose water or sanitary districts through regional authorities, interstate compacts and federal river basin agencies. An important general reference is Davies (72). An excellent case study of the functioning of such multiple political institutions in the complex Los Angeles area has been compiled by Warren (73); Mann (74) has studied Arizona. Various proposals for different political arrangements have been published; notable is Kneese's (26) description of the functioning of regional water resource/quality cooperatives in the Ruhr.

There have been various attempts at sociological analysis of water-related institutions and water interest groups; perhaps the most ambitious is the attempt to develop a quantitative model of institutional behavior by Males et alia (75*) for the case of a California Regional Water Quality Control Board. The National Water Commission (76) is publishing a survey of public reactions to water problems and policies. By and large, these attempts are not directly usuable in systems analysis due to lack of validation. Nevertheless, it is certainly important for the analyst to understand clearly the interest groups and institutional history relevant to water quality in any given region under analysis.

3. Economic Issues in Water Quality Analysis

A background in the overall economics of water is essential for accomplishing useful systems analysis in water quality. Of particular importance is an understanding of the economic impact of water on the development, growth and prosperity of regions and industries, as well as the conflict of regional economic interest with national economic interest. Important general references here are Maas et alia (77) and Smith and Castle (78). In the specific area of economics of water quality, major references are Kneese (26), Jarret (80) and FWPCA (81). Howe and Easter (82) have dealt with the more specialized subject of interbasin transfers; their book is valuable for the variety of construction cost data and economic benefit data (particularly for agriculture) presented. It is particularly important that the analyst be familiar with the areas of economic benefit that have been usefully quantified and those that have not. Extensive and useful regional analysis of agricultural economic benefits has been accomplished for irrigated regions in the West; e.g., Heaney (9*) has modeled water benefits and optimum allocation for 44 regions in the Colorado River Basin. However, indirect or multiplier benefits beyond direct gross value-added measures remain highly uncertain. Direct economic benefits of water for Eastern agriculture have not been studied intensively and little data is available to the analyst. Industrial economic behavior with respect to water quantity, price and quality variations, though understood in theory, has generally not been reduced to empirical, numerical results useful for water quality planning. Recreational benefits have neen extensively studied and at least useful lower bounds on the dollar value of recreational use have been estimated; general references in this area are Knetsch (83) and Davis (84).

In long range water quality planning, projections of water use and quality as related to economic and demographic considerations are an essential input. A good appreciation of the uncertainties and weaknesses involved in such projections can be obtained from Wollman (24) for national projections and Goldstone et alia (85*) for detailed regional projections of the Susquehanna River Basin.

A special topic of interest in water quality economics is the question of direct regulation of discharges versus effluent changes and/or subsidies. Besides the major review by Kneese (26), Upton (86*) addresses the question of optimal taxation in the absence of knowledge of individual discharge cost functions. Johnson (10*) computes actual charges necessary to achieve prescribed DO standards for the Delaware Estuary, based on estimates of discharger treatment costs and simplified assumptions concerning industrial responses.

A final major economic input to water quality analysis is the area of costs, particularly costs of low-flow augmentation, in-stream aeration, centralized and individual discharger treatment/disposal. Basin references in this area are FWPCA (87) and (88). Costs for in-stream aeration are given in Davis (89); details of biological treatment costs can be found in Smith (91) and Parker (35*); generalized costs of reservoir storage are given in Maas et alia (77) and Howe and Easter (82). Needless to say, the precision of cost estimates in these areas is relatively poor; it is essential for the analyst to have an appreciation of the range of uncertainty in each case.

Important areas in which almost no cost data base is available are the direct costs of pollutional damage to downstream users and the costs of industrial pollution abatement versus improved housekeeping or process changes. These can and have effected surprisingly large reductions in pollutant loads for a substantial number of plants at low or even negative cost; ignoring the possibility of major industrial pollution abatement without the normally assumed capital investment in standard treatment facilities is a serious source of cost overestimation in most assessments.

SECTION VI

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SECTION VII

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PART II - ABSTRACTS

SECTION A

INTRODUCTION TO ABSTRACTED PAPERS AND PROGRAMS

The paper and programs selected for inclusion in this section are intended to be a representative sampling of current work and emphases in systems analysis of water quality. The abstracts themselves are more detailed and more critical than the usual practice in scientific abstracts. This approach has been taken to allow the abstracts to serve as a balanced introduction to both the capabilities and the limitations of systems analysis in water quality planning, management and operations.

SECTION B

BASIN AND STREAM MODELS FOR ALLOCATION OF ABATEMENT RESOURCES - ABSTRACTED PAPERS

Author and Title	Page
Anderson, N.W., and Day, H.J., "Regional Management of Water Quality - A Systems Approach"	B-2
Dysart, B.C., III, "An Economic Approach to Regional Industrial Waste Management"	B-4
Graves, G.W., Hatfield, G.B., and Whinston, A., "Water Pollution Control Using By-Pass Piping"	B-6
Joere, E.F.,"An Operations Research Approach to Basin Sediment Control"	B-8
Johnson, E.L., "A Study in the Economics of Water Quality Management"	B-10
Liebman, J.C., "A Branch-and-Bound Algorthim for Minimizing the Costs of Waste Treatment, Subject to Equity Constraints"	B-14
Montgomery, M.M. and Lynn, W.R., "Analysis of Sewage Treatment Systems by Simulation"	B-17
Reid, G.W., et.al., "Model of Optimal Combination of Treatment and Dilution"	B-19
ReVelle, C.S., Loucks, D.P., and Lynn, W.R., "A Management Model for Water Quality Control"	B-23
Water Resources Engineers, Inc., Systems Analysis of Urban Water Management	B-25

Anderson, N. W. and Day, H. J., "Regional Management of Water Quality - A Systems Approach", Journal Water Pollution Control Federation, Vol. 40, No. 10, pp. 1679-1687, October 1968.

DESCRIPTORS

OBJECTIVE

This paper deals with an investigation of regional management of organic pollution in the Great Miami basin of Southwestern Ohio using both linear programming and simulation techniques. The objective of the study was to determine individual plant monthly treatment levels necessary to minimize regional operating costs (excluding investment costs and amortization) of conventional waste treatment (BOD removal) without violating river standards (D.O. level).

MODEL/METHOD

An oxygen sag model for the Miami River was developed using the modified Streeter-Phelps linear differential equations to describe DO deficit at various locations along the river in one-dimensional terms. The river was divided into short uniform reaches and the sag model was used to determine linear "influence" coefficients relating individual discharge treatment efficiency to oxygen deficits in downstream reaches. A standard linear programming format is adapted to minimizing the sum of treatment operating costs while meeting oxygen deficit constraints with monthly treatment efficiency policies. These policies are then tested in a simulation using 400 years of synthetic flows to compare frequency of violation of standards among policies.

ASSUMPTIONS MADE

1. The river system can be approximated in terms of a series of short uniform reaches
2. The effect of upstream pollution loads on each reach can be described by linear coefficients based on a modified form of the Streeter-Phelps equation
3. The level of BOD reduction at a particular plant can be varied uniformly from 45 to 90% each month and operating costs for each month will vary in direct proportion to BOD reduction.

DATA REQUIRED

1. Number of reaches, length of reaches, and location of waste outfall;
2. Waste loadings received by treatment facilities;
3. Treatment efficiencies available at each outfall;

4. Operating cost vs. efficiency at each waste treatment facility;
5. Quantity, velocity and quality of main and tributary flows in each reach;
6. Deoxygenation and reoxygenation coefficients;
7. River standards for dissolved oxygen in each reach.

RESULTS/COMMENTS

A claimed saving of 40% in operating costs over a uniform 85% removal effluent standard is claimed for the derived optimum policy with standard compliance 96% of the time. However, severe restrictions on the model and findings exist:

1. Variability other than that associated with extreme low river flow such as waste loads, temperature and DO is not included.
2. In some cases operating cost and average BOD reduction were synthesized from other facilities instead of actual data. Cost was linearized based on reported yearly operating costs and removal efficiency. It is by no means clear that operating for costs treatment plants have much flexibility on a month-to-month basis. Furthermore, the model cannot trade investment costs for new facilities against existing operating costs; this is certainly necessary to achieve overall regional optimization.
3. Effects of photosynthesis and benthic deposits are included only by means of fitted deoxygenation and reoxygenation coefficients in each reach. Fixed contributions of BOD from runoff are not included. The potentially substantial cost of treatment for meeting standards other than DO are not incorporated.

The formulation of treatment and costs in this manner does not correspond to the real world of today. For though it is possible to operate a treatment plant at any particular level of a wide efficiency range, this is not normally done nor is it clear that significant cost savings (relative to total life-cycle cost) are feasible through operating efficiencies below design level.

RELATED REFERENCES

1. Anderson, M. W., "Regional Water Quality Management in the Miami Basin," Ph.D. Dissertation, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1967).

Dysart, B.C., III, "An Economic Approach to Regional Industrial Waste Management,: Proceedings of the 24th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1969.

DESCRIPTORS

OBJECTIVE

The study demonstrates an economic approach to regional industrial waste management. The modeling technique employed involves discrete, one-dimensional dynamic programming. Two principal problem areas are addressed:

1. Allocation of resources in which the objective is to minimize economic costs (i.e., optimize the treatment levels) of a multiple-facility basin system within dissolved oxygen standards as constraints.
2. Investigation of response or sensitivity of the minimum total system costs and the optimum management policy to system variation.

MODEL/METHOD

The approach is illustrated by a hypothetical river basin system involving three stream reaches (stages) in series. An industrial waste outfall is located at the head of each reach. The Streeter-Phelps formulation is used to compute the transfer function relating upstream BOD and DO inputs to downstream BOD and DO concentrations in each computation, the program checks for each reach that the minimum DO is above the reach DO standard and yields the input BOD and DO for the next reach.

The dynamic program written starts with coarse increments in treatment level, input BOD and input DO and reduces increment size on each iteration.

ASSUMPTIONS MADE

1. Steady state is assumed with regard to waste production at each discharge and with respect to stream flow.
2. Deoxygenation and reaeration can be represented by first-order processes and the basic Streeter-Phelps dissolved oxygen sag equation is applicable.
3. DO is the pollutant standard that dominates total regional treatment costs.

FACTORS INCLUDED

Factors included in the policy-optimization, minimum cost phase of the study are waste production and waste treatment levels, costs at each discharge, stream BOD/DO balance, flows by reach and BOD/DO inputs at head of stream system. Factors examined in the sensitivity analysis phase include varying dissolved oxygen standards, varying streamflow (i.e., effect of augmented flow) and total costs.

DATA REQUIRED

1. Waste production at each industrial site in terms of BOD per unit of time.
2. Cost data for various levels of treatment at each industrial site.
3. BOD and DO concentrations entering at the upstream end of the system.
4. Mean stream flow rates within each reach.
5. Deoxygenation and reaeration coefficients for each reach.

RESULTS/COMMENTS

An example of minimum cost assessment is presented using hypothetical data in a hypothetical three-stage river basin system. Three iterations of the standard dynamic programming search procedure using successively smaller increments of treatment levels, input BOD, and input DO converged effectively on the optimal policy to produce minimum cost. Cost and policy sensitivity to system changes are analyzed for potential incremental adjustments of streamflow and DO standards. The response of optimal cost to variations of streamflow and standards, and the response of optimal treatment levels to the same parameters are presented in graphical format for consideration by authorities in making rational policy decisions. For the example shown, sensitivity to small changes in standard was high, while sizable changes in streamflow had surprisingly small effects.

The hypothetical basin system with simplifying assumptions is adequate to illustrate the methodology. However, none of the stated assumptions is completely realistic. In any adaption of the method to a real situation, time varying and/or stochastic measures of waste production, streamflow, oxygen sag, and physical stream conditions should be considered. Stage transfer functions involving additional factors such as algal and benthic take-up of oxygen and photosynthesis contributions to DO levels are becoming available and should be considered. The methodology may be suitable for addressing multiple pollutant standards, an important consideration for achieving realistic total cost minimization.

Graves, G.W., Hatfield, G.B., and Whinston, A., "Water Pollution Control Using By-Pass Piping", Water Resources Research, Vol. 5, No. 1, Feb., 1969.

OBJECTIVE

To demonstrate the cost of savings possible using optimum arrangements of bypass piping to achieve desired minimum DO standards in the Delaware Esturay.

MODEL/METHOD

The Thomann-Marks programming formulation was used in attempt to determine the minimum cost bypass piping configuration for achieving the desired DO standards. Due to the number of variables and constraints a special large scale programming technique was developed and applied.

FACTORS INCLUDED

1. Only various bypass configurations are considered; no combinations of treatment and bypass are handled by the model.
2. The Thomann-Marks formulation of linear transfer coefficients between BOD discharges and DO levels in each reach of the estuary is used.
3. Cost savings through joint rather than redundant pipeline sections are considered.

ASSUMPTIONS

1. Empirical pipeline cost relations are assumed; no extra costs for river cross-overs or urban areas are assessed.
2. Steady-state, linear deoxygenation/reaeration rates as required by the Thomann-Marks formulation are assumed.
3. Optimum joint pipeline configuration can be determined by inspection (the model does not eliminate duplicate piping automatically).
4. DO degradations in above-minimum reaches will be permitted (these constitute violations of current anti-degradation regulations).

RESULTS/COMMENTS

The optimal levels and discharge locations for major pollutors along the Delaware River have been determined using the Thomann-Marks model. The sensitivity of the cost minimizing solutions has been determined; it is found that for fixed waste loads and costs the solutions are particularly sensitive to the reaeration coefficients and much less sensitive to diffusion and decay terms. The paper indicates the marginal savings achieved through bypass piping as compared with on-site treatment, amounting to one to two orders of magnitude.

SIMILAR/RELATED REFERENCES

Thomann, R.V., and Marks, D.H., "Results from a Systems Analysis Approach to the Optimum Control of Estuarine Water Quality", Third Conference of the International Association on Water Pollution, Munich, Germany, September, 1966

Joeres, E. F., "An Operations Research Approach to Basin Sediment Control," Third American Water Resources Conference Proceedings, American Water Resources Association, Urbana, Illinois, November, 1967.

DESCRIPTORS

OBJECTIVE

The paper presents a scheme for minimizing the total cost of basin sediment control and sediment damages resulting from a greatly increased basin load due to new upstream construction.

MODEL/METHOD

A dynamic programming model is developed in consideration of a basin comprised of an estuary, a main stream, an upstream sediment-producing construction site, a tributary, and a reservoir. The basin is divided into five stages; each stage incurs a cost for sediment control as a non-linear function of amount trapped plus another cost for sediment damage in that stage's reach. Stage transfer functions are written starting at the downstream end. At each stage, the cumulative cost of all downstream damages is minimized relative to the sediment control decision(s) available in that stage, taking into account optimization in prior downstream stages. This process relates downstream optimum stage control decisions to the control decision at the upstream construction site; iterations of the latter decision then converge on the best at-site control effort to minimize basin cost.

ASSUMPTIONS MADE

1. The sediment yield resulting from construction activity in the upstream reach is a fixed total amount which is known.
2. Prior to the development situation, an equilibrium condition existed and few or no control measures were needed.
3. Sediment damage costs in each reach are known (e.g., dredging, stream overflow, industrial pre-treatment requirements, drain clogging, pumping failures, etc.)
4. The decision as to the degree of control to be provided at a particular location and the damage caused downstream by bypassed sediment are independent of the size distribution of the incoming sediment load (problem exists due to preferential settling of heavier particles).

5. The reservoir size is small; thus its sediment trap efficiency can vary widely and be considered a control decision variable.

FACTORS INCLUDED

Sediment loads, settling rates, control options, and costs, sediment damages.

DATA REQUIRED

1. Cost-treatment functions for all measures taken at each control point.
2. Cost-damage functions resulting in each reach as a result of sediment allowed to pass the control point.
3. Sediment sources and loads.

RESULTS/COMMENTS

A numerical example is not included as part of the model development. Stage return functions, stage transfer functions, and stage optimum cost functions are developed conceptually for each zone of the basin in terms of sediment load reaching or generated at a given location, the decision made at that location concerning the degree of sediment control to impose, and the total costs associated with the decision.

Inclusion of random variation in loads (due to rainfall and streamflow variability) causes grave difficulties for the dynamic programming approach. However, if the stage returns for all stages are quadratic expressions and all stage transformations are linear, the problem can be transformed back to an essentially deterministic problem using simply expected values of each random variable.

The model development is simplified to illustrate the application of the technique. In reality, many sediment sources will prevail, the rates of sediment yield will vary with time as a complex function of other variables in addition to rainfall, and the total amounts of sediment releasable cannot be fixed except in very special cases. Long-range projections of sediment producing activities (instead of optimizations for one-shot construction) will be needed to achieve a realistic optimization of a large basin system. Long-range projections of water user requirements and associated damage potential in light of anticipated technological advances are also required. Since comprehensive estimates of sediment damage for any basin have not been accomplished, it is not known whether it is possible to develop the requisite cost data.

Johnson, E.L., "A Study in the Economics of Water Quality Management", Water Resources Research, Volume 3, No. 2, Second Quarter 1967.

DESCRIPTORS

OBJECTIVE

Purpose of this report is to present and compare several methods of allocating waste reductions among dischargers using Delaware Estuary Study data. Specifically, this study sought to demonstrate the effluent charge (in terms of $/lb. of BOD) required to attain each of several desired levels of DO, assuming steady state conditions.

MODEL/METHOD

Four policies were considered:

1. Uniform treatment (UT) - all dischargers must remove a specified equal proportion of their respective waste loads before discharging to the water body.

2. Least cost (LG) - allowable waste discharges are allocated on the basis of marginal costs of increasing removal efficiency in such a manner as to minimize the total (basinwide) cost of meeting a dissolved oxygen goal.

3. Single effluent charge (SECH) - a uniform price per unit of oxygen-demanding material discharged to the water body is applied to each waste source.

4. Zone effluent charge (ZECH) - an effluent charge constant within zones is levied on each unit of oxygen-demanding material discharged.

All solutions must satisfy the basic physical constraints:

1. Additional waste removal must be sufficient to meet the specified quality improvement.
2. Removals must be zero or positive; that is, no one is allowed to reduce his level of waste removal.
3. The total amount of waste removed by any discharger, the sum of the current plus ad-

ditional removals must be less than his total load before any removal; (i.e., each discharger cannot reduce his waste discharge by more than 100%).

Additional conditions are imposed on the three basic constraints to form computational models for each of the load allocation techniques.

a. The program (UT) selects a vector f such that the basic constraints are satisfied and all dischargers additionally remove the same proportion of their raw wastes before discharging, except that those who are already removing an equal or greater proportion must continue to do so.

b. The least cost model (LC) is obtained by forming the linear programming problem which minimizes the total cost (sum of costs of each discharger) subject to the three basic constraints.

c. The model (SECH) treats the removal as a function of charge. The level of removal of each discharger induced by a charge is determined by investigating the response curve of that discharger, assuming cost minimizing behavior. SECH selects an arbitrary nominal charge for all dischargers which in turn, maps into an induced increase in removal; then it converges to a charge such that the induced waste reduction satisfies the three basic constraints.

d. The effluent charge model (ZECH) performs exactly as SECH, except that a different charge may obtain in each zone of the water body, and conceivably more than one set of such charges will induce sufficient removals to satisfy the quality improvement constraint. Therefore, an additional condition is specified that selects from among all feasible sets of charges that set which in duces the least total waste reduction expenditure and which satisfies the three basic constraints as well as the requiement that the total annual cost of the induced waste reduction should be less than or equal to the total annual cost for the current removal.

FACTORS INCLUDED

BOD/DO balance for the estaurine case, simplified cost-minimizing behavior for dischargers, Not considered explicitly were the following: storm water overflows, urban drainage, benthic and photosynthetic oxygenation effects as well as cost reduction through regional treatment alternatives.

ASSUMPTIONS MADE

1. Only steady-state conditions are considered.
2. Control authorities do not permit individual dischargers to reduce their levels of waste reduction below that currently being practiced.
3. Costs of waste reduction are not important enough to result in significant production changes.
4. Dischargers select between investment in treatment or payment of effluent charges based only on cost-minimization critera.
5. All treatment costs and quality requirements are associated only with BOD rather than other pollutants.

KEY DATA REQUIRED

Input data to each model are basically the same, consisting of: (1) a matrix relating the effect on DO level in each reach to a unit removal of oxygen-demanding material in any other reach; and (2) a piecewise linear cost function for each discharger, showing his waste removal cost.

RESULTS/COMMENTS

1. Effluent charges should be seriously considered as a method of attaining water quality improvement;
2. Cost of waste treatment induced by a zoned charge level will approach overall regional minimum cost treatment plan;
3. A charge level of 8 to 10 cents per pound of oxygen demanding material discharged appears to produce relatively high increases in critical dissolved oxygen levels;

4. Major regional economic readjustments resulting from a charge of that level are not anticipated to occur in the study area;

5. Administrative costs and difficulties of managing an effluent charge method are greater than conventional methods of quality improvement. However, the problems are not insurmountable and are not sufficiently great to negate the advantages of the charge method;

6. Compared with a conventional method of improving water quality, the charge method attains the same goal at lower costs of treatment, with a more equitable impact on polluters. Also, the charge provides a continuing incentive for the polluter to reduce his waste discharge and provides a guide to public investment decisions;

7. More study is needed of the technical problems of coping with differential charges related to transient waste load discharges prediction of induced responses, administrative problems associated with sampling of discharges, and damage estimation.

8. All four of the allocation schemes will satisfy the goal. The LC is the most efficient program for meeting the quality goal. ZECH can be made to approach the LC solution as closely as desired by increasing the number of zones, but costs of administration and data gathering would, of course, also tend to increase. The UT scheme is the most inefficient in that it not only requires unnecessary waste reductions but requires such reduction regardless of the marginal cost of undertaking them.

Liebman, J.C., "A Branch-and-Bound Algorithm for Minimizing the Costs of Waste Treatment, Subject to Equity Constraints," Proceedings of IBM Scientific Computing Symposium on Water and Air Resource Management, Oct. 1967.

DESCRIPTORS

OBJECTIVE

Purpose of this report is to minimize the regional cost of wastewater treatment to meet DO stream standards without violating subjective equity constraints (equal treatment for all dischargers in a geographical or industrial category).

MODEL/METHOD

A zoned minimization approach is followed in which dischargers are grouped into categories, an equal treatment restriction is imposed upon all the plants within each category, and the cost of the entire basin treatment is then minimized. The river basin (with or without estuary) is divided into relatively uniform reaches with a DO standard for each.

The difficulties of treating this problem by dynamic programming are shown. Next, a linear programming formulation of the problem is given which fails due to both nonlinearities and discontinuities in costs of improved treatment. This is reformulated into a 0-1 integer programming problem (in order to circumvent nonlinearities); the 0-1 variable represents the non-employment or employment of one of a preset number of discrete levels of treatment at a given plant. The objective function to be minimized is:

The summation over all categories of the cost for providing the appropriate level of treatment in each category required to meet the DO standards in all reaches. The cost function has a discrete jump at each point where the existing level of treatment at a plant is reached; this is easily represented since cost coefficients represent total cost of reaching a certain treatment level for all plants in a category.

The constraints are:

1. The sum of DO reductions in a given reach contributed by all plants should be at least equal to the required DO reduction for that reach.
2. The sum of the 0-1 indicator variable over all alternate levels of treatment for any plant should be one.

This formulation has increased the number of variables over the linear program by a factor equal to the number of discrete treatment levels. To solve the zoned problem a modified Geoffrion algorithm is used. This is a branch-and-bound technique which is used on the 0-1 integer problems. In this approach, at each iteration all of the variables of the problem are contained in one of three groups: a) those variables which are "free" (values have not been specified), b) those variables whose values has been set equal to 0 in a previous iteration, c) those variables whose value has been set equal to 1 in a previous iteration; each iteration consists of selecting a free variable and setting it equal to 1 or selecting a variable with value 1 and setting it equal to 0. In this way a "tree" of possibilities is developed. The model was applied to the Delaware Estuary with 7 categories (zones), 13 levels of treatment and 15 constraints.

FACTORS INCLUDED

Cost non-linearities including existing treatment; BOD/DO balance by reach including loads of plants outside the reach; equal treatment requirements for each discharger category.

ASSUMPTIONS MADE

a. Cost vs. treatment level for any category is monotone nondecreasing (required by Geoffrion algorithm).

b. Stream standards for all other pollutants will be met when DO standards are met (or treatment costs for other pollutants are independent of BOD treatment.)

c. DO reductions due to individual plant BOD reductions are additive in a given reach (this is only literally true if all discharges occur at a point.)

DATA REQUIRED

Reach and category definitions, DO standards by reach, effect on each reach of BOD reduction at every plant, total cost by discharger category of implementing each level of treatment.

RESULTS/COMMENTS

The application of zoned treatment requirements using this model in the Delaware case gave an overall cost of \$116.6M as contrasted with \$78M for a minimum cost solution with no need for equal treatment and $157M for regionally uniform treatment. A zone treatment approach for planning problems on a river basin leads to sufficient flexibility to permit subjective notions of equity to be introduced into the solution at considerably lower cost than uniform treatment. The branch and bound algorithm is a feasible method of solving such problems, though running time was 27 minutes for the Delaware case using an IBM 7094.

The method stands or falls on the extent to which DO dominates total cost of meeting water quality standards and on the accuracy of predicting oxygen sag due to an individual discharger's load.

Montgomery, M.M. and Lynn, W.R. "Analysis of Sewage Treatment Systems by Simulation", A.S.C.E. Journal of the Sanitary Engineering Division, Vol. 90. No. 1, 1964.

DESCRIPTORS

OBJECTIVE

This paper deals with a sewage treatment system that includes the possibility of using effluent storage and low-flow augmentation. Objective of the study was to develop insight into the operation of the system using various combinations of "treatment" elements and operating disciplines and to measure the resulting frequency of stream quality violations.

MODEL/METHOD

The description which follows is applicable for a single sewage treatment plant discharge and continuous stream flow.

The elements of the model are: treatment plant, effluent storage reservoir and stream augmentation reservoir. Inputs are randomly varying sewage flow, sewage strength, and stream flow. These demands are handled in standard queueing theory format. The treatment plant accepts immediately all arrivals of sewage input. The plant changes the characteristics of the arriving sewage and then releases it to the effluent storage reservoir. The degree of treatment is described by operating curves that depend on the retention time and strength. Since the treatment plant essentially operates at full capacity (such that the treatment costs will be minimized) every arrival forces an equal quantity to be released (into the effluent storage reservoir, when employed). For a given arrival, the rate of subsequent arrivals determines the detention time.

The effluent storage reservoir releases only an amount of effluent that will not violate the stream's maximum allowable oxygen deficit (as determined by a Streeter-Phelps oxygen sag formulation), given the effluent resevoir is below capacity.

The capacity of the stream (actually the distribution of its capacity over time) is varied by the introduction of the low-flow augmentation reservoir. The reservoir release is a function of the normal stream flow and the demand for release as dictated by the requirement to accept effluent from the sewage treatment plant.

The digital simulation program is constructed so that it may be operated in any one of four configurations: treatment plant/stream; treatment plant/augmentation reservoir/stream; treatment plant/effluent storage/stream; and treatment plant/augmentation reservoir/effluent storage/stream.

Varying capacities and operating rules may be studied using synthetic stream hydrology and synthesized sewage flows and strengths (normally distributed around diurnal cycles).

FACTORS INCLUDED

Stream standards and assimilative capacity, variable stream flows/sewage flows and strength.

KEY ASSUMPTIONS

1) Uniform quantity and quality of flow exists in both the stream and sewage for the duration of one simulation time period.
2) "Plug-flow" is assumed such that a quantity of sewage flow entering the plant in a period is not mixed with sewage that had arrived in earlier periods.
3) BOD concentration of the entering sewage is independent of the sewage flow.
4) Stream reoxygenation and reaeration rates plus input stream DO remain constant at all flows (not in accordance with observed stream characteristics).

KEY DATA REQUIRED

Stream hydrographs, sewage flow statistics, sewage BOD concentration statistics, initial DOD in the stream, reaeration and reoxygenation coefficients, plant operating curves as function of detention time and BOD influent.

RESULTS/COMMENTS

Comparing the four configurations (based on hypothetical data) the plant/ stream system yielded standard violations 10% of the time; 8% for plant/effluent reservoir/stream; 1.4% for plant/augmentation/stream and 1% for all four components. Utilization of total stream assimilative capacity varied only slightly. Given more realistic formulations of plant behavior and of stream assimilative capacity with flow plus the addition of cost considerations, the queuing simulation approach appears to be one of the more promising methods for considering variability in stream systems with small numbers of discharges.

Reid, G.W., et.al. "Model of Optimal Combination of Treatment and Dilution," Proceedings of the Third Annual American Water Resources Conference, San Francisco, Nov., 1967, pp. 339-350.

DESCRIPTORS

OBJECTIVE

The ultimate objective of this continuing work is the development of nationwide input-output model relationships that will cover all major pollutant categories in sufficient detail to address specific basin storage project issues. The specific objective of this study is the development of dilution requirements as a function of municipal and industrial waste treatment levels by basin for use in setting low flow augmentation requirements that minimize the cost of dilution plus treatment. This forms an input to the Wollman Supply-Demand Model for national assessments. The study develops stream response sub-models for each of 6 major pollutant categories.

MODEL/METHOD

General problem constraints:

1. Economic projections are provided in aggregate terms for a basin.
2. Physical stream characteristics are fixed and known (including seasonal variations).
3. In-stream water quality standards are given.

Major factors included in the study are those related to consideration of the following pollutant categories:

1. Organic oxygen demanding substances (biodegradable wastes)
2. Infectious agents (bacterial)
3. Plant nutrients (aggregated eutrophication - N and P)
4. Persistent chemicals (conservative substances -- brines, metallic ions, etc.)

5. Heat (thermal pollution)
6. Sediment (suspended solids)

Specific component models are not developed for sediment and infectious agents; they are considered as additional constraints (minimum standards) in the overall systems model. Input-output (dilution flow required vs. treatment level and loads) relationships are developed for each of the four remaining pollutant categories.

Biodegradable Model

The domestic waste load on a stream is expressed for the total basin load in terms of population equivalents and the fraction of waste load discharges after treatment. The model includes a linear (Streeter-Phelps) estimate of BOD assimilation capacity of a given river system (depending on basin-wide reaeration constraints, average branching effects and average point-to-uniform loading ratios derived from urban population fraction, plus a single oxygen demand rate for all BOD). Industrial loads are incorporated analagously, with projections based on national economic growth and a statistical survey of waste loads per unit production. Estimated constants are given for each of twenty-two major stream basins of the United States.

Accelerated Eutrophication Model

Parallel models are developed for both nitrogenous and phosphorus nutrients. The models are simple mass balances of N or P removed by treatment plus the N or P removed by in-stream bacterial action; the remaining quantity is used to compute a concentration in the fraction of the basin flow that is impounded (since water storage areas are the critical zones in terms of algal blooms). Dilution flow requirements to reduce the concentration to an acceptable Oswald AGP index (Algal Growth Potential) are computed, based on both average N and P loads per capita and projected industrial loads (based on estimated N and P raw load per unit production) for each basin.

Thermal Model

A simple basin-wide thermal mixing model is derived in terms of waste flow and temperature differential, basin-wide allowable stream temperature changes, and basin-wide mixing constants. The model computes dilution flow required to meet basin standards of allowable temperature increases over normal maximum summer temperatures.

Conserved or Persistent Chemical Waste Model

The persistent waste model simply computes the dilution necessary to reduce persistent chemical concentrations to a basin standard, given the chemical loads and the standards for each persistent pollutant.

ASSUMPTIONS MADE

1. Biodegradable model: linear stream oxygen balance with basin-wide average parameters has usable accuracy. Benthic demand, photosynthesis and run-off BOD (independent of population and industry) can be ignored.

2. Eutrophication model: basin-wide average water storage conditions related to AGP index (based only on the worse of N or P) are adequate to compute treatment and flows required to prevent eutrophication. Organic carbon, temperature and salinity interactions can be ignored.

3. Thermal model: basin-wide average mixing conditions and basin-wide standards are adequate to balance effluent cooling against flow augmentation for prevention of thermal damage.

4. Persistent chemicals model -- standards and loads in each important category of persistent chemicals (e.g., mercury, chlorinated hydrocarbons, brines, etc.) can be defined on a basin-wide basis. Natural (or population industry unrelated) fixed sources can be ignored.

5. In general, reasonable and quantitative basin-wide water standards can be defined and projected for 30 years, despite the multiplicity and vagueness of current standards within any given basin.

RESULTS/COMMENTS

The component models are to be integrated into a computer system for use in basin analyses. Analysis is to be performed by considering the optimal treatment of pollutants (i.e., four types) and augmented flow rates to produce a minimum cost solution for meeting the water quality standards established for each pollutant. Basin-wide costs are assigned to each of four levels of treatment (secondary, nitrogen removal, phosphorus removal and tertiary treatment) plus to each of the low flow augmentation storage requirements associated with each treatment level.

Details of the development of the basin-wide constants and load projections are not included in the present work. No validation of the component models is presented.

The input-output models may provide estimates suitable for assessing long-range water resource requirements on a gross national basis. The severe assumptions and basin-wide approximations involved in the method reduce the probable accuracy of the results to a questionable level for optimization of water resources and minimization of costs or sub-basin or individual project levels.

SIMILAR/RELATED REFERENCES

1. Reid, G.W., "Low Flow Augmentation Requirements," Committee Print No. 29, U.S. Senate Select Committee on Water Resources, 1959.

ReVelle, C.S., Loucks, D.P. and Lynn, W.R., "A Management Model for Water Quality Control," Journal Water Pollution Control Federation, 39(7), 1164-1183, (1967).

DESCRIPTORS

OBJECTIVE

A model based on linear programming and the oxygen-sag equation is presented which determines the degree of treatment required from individual waste water dischargers in such a fashion that the total treatment cost is minimum and the stream standards are met.

MODEL/METHOD

For convenience the river is divided into reaches with one discharger at the head of each reach. In each reach is an arbitrary number of control points for checking oxygen sag. The objective total cost function that is to be minimized is the sum of individual treatment costs, each linear with respect to BOD removal.

The linear constraints are as follows:

1) In each reach the treatment efficiency plus the effluent BOD concentration divided by the influent BOD concentration sums to 1.

2) A mass balance equation is written at the head of each reach for the oxygen deficit.

3) A mass balance equation is written at the head of each for the BOD.

4) The treatment plant efficiency must fall within a given range (35-90%) to preserve treatment cost linearity.

5) The oxygen deficit at the top of each reach and at each control point (sags calculated from the classical linear Streeter-Phelps equation) must be at most equal to the maximum deficit allowed by the reach standard. These constraints are linear in load and deficit at the head of each reach.

FACTORS INCLUDED

BOD, DO

ASSUMPTIONS MADE

1) Cost of treatment is linear vs. efficiency within the range 35-90% removal.

2) Perfect mixing of the waste water and stream flow occurs at the beginning of each reach.

3) The bioxidation rate at each reach is an accumulative average of the rates of wastes of the previous reaches (including this last one - the linear ozygen sag differential equations are valid.

4) Oxygen sag control points are close enough together to prevent significant violations from occuring between them.

KEY DATA REQUIRED

Bioxidation constant, reaeration constant, slope and intercept of individual treatment cost curves, discharge and stream flows, and BOD loads and DO standards.

RESULTS/COMMENTS

The advantages of this procedure are:

a) The algebra of the constraints, especially the inventory equations, provides a consise and clear statement of the relations of variables.

b) There is no limitation as to configuration of the river system; tributaries are easily handled.

c) Standard linear programming software packages can be used.

There are, however, significant problems with this formulation including possibly serious non-linearities of treatment cost, the inequity of applying different treatment standards to discharges depending on their location and proximity to other dischargers, excessive computational load for any sizable industrialized region, and the lack of realism in setting effluent treatment requirements based on BOD as the only significant pollutant.

SIMILAR/RELATED REFERENCES

1) Deininger, R. A., "Water Quality Management - The Planning of Economically Optimal Pollution Control Systems," Systems Research Memorandum, No. 125, Northwestern Univ., Evanston, Ill., The Technological Institute (1965).

2) Liebman, J. C., "The Optimal Allocation of Stream Dissolved Oxygen Resources," Doctoral Thesis, Cornell Univ., Ithaca, N. Y. (1965).

3) ReVelle, C. S., Loucks, D. P., and Lynn, W. R., "Linear Programming Applied to Water Quality Management," Water Resources Research, Vol. 4, No. 1, February, 1968.

4) ReVelle, C. S., Dietrich, G. and Stensel, D., "The Improvement of Water Quality under a Financial Constraint - A Commentary on Linear Programming Applied to Water Quality Management," Water Resources Research, Vol. 5, No. 2, April, 1969.

Water Resources Engineers, Inc., Systems Analysis for Urban Water Management. Office of Water Resources Research, Department of the Interior, by Water Resources Engineers, Inc., September, 1970.

DESCRIPTORS

OBJECTIVE

The study is limited to a demonstration of the systems concept as a viable guide for planning, implementation, and operation of total metropolitan water resource (covering inflows, storage, outflows and quality at each stage) systems, and for fundamental research.

MODEL/METHODS

The modeling technique involves simulation of the behavior of a pilot urban system (includes river hydrology/quality, storm sewer system/urban hydrology, storage, water supply treatment, user systems with reclamation treatment possibilities, waste collection, waste treatment with reclamation alternative, and disposal system). These sub-systems are represented by highly simplified equations; the model computes the stepwise solution of this large number of approximate simulation equations in a sequence of monthly time periods.

In addition to the overall engineering/physical simulation model,smaller-scale economic models are developed to compute benefits and costs for two specific selected subsystems using technical outputs of the engineering model as basic input information.

ASSUMPTIONS MADE

Key assumptions and approximations of the model development include:

1. The feedback and interactions as simulated for a limited set of sub-systems are representative of complex interactions that will occur in a comprehensive simulation of all aspects of urban water.

2. The gross operational and economic functions assumed for illustration in the study are adequate for water quality system evaluations in general or, if more complex functions are required, they can be evaluated satisfactorily by the stepwise solution of the approximate equations.

DATA REQUIRED

Direct application of the methodology to existing situations would require the development of specific situation-appropriate technical and cost data as follows:

1. Information on physical interrelationships of facilities
2. Monthly rainfall quantities and qualities
3. Monthly stream flows and/or groundwater hydrology
4. Monthly water quantity and quality demands of all users
5. Available import quantities and qualities
6. Value of water at specified qualities to each user
7. Capital, operational and maintenance costs for treatment and delivery of water quantities and qualities
8. Present work factors and capital recovery factors
9. Factors to accommodate intangible benefits.

RESULTS/COMMENTS

The physical models developed produced only gross simulation of urban water systems behavior. Other work by the authors dealing with the feasibility and current successes of increasing the detail of simulation to represent realistically the time varying behavior of each sybsystem is summarized.

Several components of the technical evaluation model are developed for demonstration and applied to a hypothetical urban system (with hypothetical input data) comprised of three separate users, three import sources each containing five quality constituents, facilities for storage and treatment of water, and waste-water reclamation facilities for each user. Economic modeling demonstration was performed for only one combination of import source yields and user demands. Four analyses were made for a schedule of waste removal efficiencies involving three different types of treatment. Economic evaluation was performed for water use and water treatment examples. Results of both technical and economic evaluations are included in the report in tabular form.

The authors believe the model development format is general enough to permit its application to multiple urban water systems comprising a region or a basin and that the method may be extended to include social, demographic, and political models along with the technical and economic components. In addition, an executive simulation-optimization program is recommended.

This study suffices as a basic demonstration of ability to model a logical sequence of events taking place in a simplified metropolitan water system. The models developed may be practical as a tool for limited examination of sensitivity of subsystem performance or of costs to gross changes. They would become very cumbersome, even with computers, if applied to the overall optimization of water supply, water treatment and waste treatment costs, benefits, and consequences for a real major urban location, much less a multiple-facility multiple-use basin system. Furthermore, the use of 30 day evaluation steps may prove unacceptable for evaluating subsystem interactions which involve critical factors of widely varying periodicity down to cycles as short as half-hour storms.

SIMILAR/RELATED REFERENCES

1. Water Resources Engineers, Inc. "Comprehensive Systems Study Engineering Analysis of All Aspects of Urban Water, A Prefeasibility Study," Appendix H, Urban Water Resources Research, First Year Report to OWRR, ASCE Urban Hydrology Research Council, September, 1968.

Andrews, J.F., "A Dynamic Model of the Anaerobic Digestion Process," Proceedings of the 23rd Industrial Waste Conference, 1968, Part I, Purdue University, 1968.

DESCRIPTORS

OBJECTIVE

This paper presents a dynamic model for the anaerobic digestion process to be used in analyzing start-up, bulking and other transient instability problems in anaerobic treatment.

MODEL/METHOD

This model uses an inhibitory function to relate unionized volatile acid concentration and specific growth rate for the methane bacteria assuming the unionized acid as the growth limiting substance and inhibiting agent. This consideration resolves the conflict existing between volatile acid inhibition and pH inhibition since the concentration of unionized acid is a function of both total volatile acid and pH. A pair of first order differential equations are used to describe organism growth and substrate concentration. Since an inhibition function is used, the model can predict growth lag variations in batch processes and failures of continous flow processes at residence times exceeding the "wash out" residence time.

Experimental laboratory reactor evidence and evidence from the bacteriological literature are presented in support of the model. Using the model to simulate both batch and continous flow systems provides additional supporting evidence by predicting results which are commonly observed in the field (e.g., increasing pH to improve stability and decrease starting time; use of 'ramp' load increases rather than step inputs to avoid digester failure; dilution to save a failing digester, etc.).

FACTORS INCLUDED

Time varying growth rate, behavior of methane bacteria, and limiting substrate concentrations in the absence of inhibition, inhibition effect.

FACTORS NOT INCLUDED

Effect of 1) organism death, 2) utilization of substrate for maintenance energy, 3) inhibition by other substances, 4) delay of organism response to changes in substrate concentration, 5) modeling of acid-producing bacteria which provide substrate for methane bacteria, 6) decrease in pH due to increase in volatile acids, and 7) known differences in inhibitory effects of the various volatile acids.

SECTION C

TREATMENT PLANT AND TREATMENT PROCESS MODELS - ABSTRACTED PAPERS

Author and Title Page

Andrews, J.F., "A Dynamic Model of the Anaerobic Digestion Process" C-2

DeBruhl, J.M. and Smallwood, C., Jr., "The Applicability of Optimization Techniques in Textile Mill Waste Treatment" C-4

Eliassen, R. and Tchobanoglous, G., "Removal of Nitrogen and Phosphorus" C-6

Erickson, L.E., Ho, V.S. and Fan, L.T., "Modeling and Optimization of Step Aeration Waste Treatment Systems" C-7

Galler, W.S. and Gotaas, H.B., "Optimization Analysis for Biological Filter Design" C-9

Meier, W.L., Lawless, R.W., and Beightler, C.S., "Geometric Programming: New Optimization Technique for Water Resource Analysts" C-12

Parker, D.S., Monser, J.R., and Spicher, R.G., "Unit Process Performance Modeling and Economics for Cannery Waste Treatment" C-14

Pearson, E.A., "Kinetics of Biological Treatment" C-16

Smith, R., "Preliminary Design of Wastewater Treatment Systems" C-19

ASSUMPTIONS MADE

Simplifying assumptions include:

a) Linear growth rates and linear inhibition effects (using the assumed inhibition functional form).
b) Omission of lag phase, organism death, endogenous respiration, use of substrate for maintenance energy or inhibition byproducts.
c) Bacterial volatile acid production rates do not constrain methane bacteria processes.
d) Digester pH control eliminates change in pH with volatile concentrations changes.
e) Differences in inhibitory effect of different volatile acids can be averaged through single invariant inhibition constant.

DATA REQUIRED

Maximum specific growth rate, limiting substrate concentration, saturation constant, yield coefficient, ionization constant and inhibition constant for the bacterial conversion of volatile acids to methane.

RESULTS/COMMENTS

The model indicates that:

1) Increasing the quantity of seed sludge or increasing pH (up to 7.3) will decrease the time required for batch digestion and start-up time for continuous flow digestion;
2) Digester failure may occur a) if insufficient seed sludge is present; b) if the pH is too low when a continuous flow digester is started; or c) if step increases in loading are applied;
3) Digester failure during start-up may be avoided by slowly bringing the digester loading to its full value; and
4) pH control and/or decrease of process loading are effective techniques for "curing" a failing digester.

The studies presented here should be considered semi-quantitative in nature since reliable values of the growth parameters are not available. Estimates were made from laboratory data presented by Lawrence and McCarthy. Growth parameters in the pilot reactor runs conducted for model verification were not estimated. The inhibition function will require modification so that it will include the factors mentioned previously as omitted.

DeBruhl, J.M., Smallwood, C.,Jr., "The Applicability of Optimization Techniques in Textile Mill Waste Treatment", Proceedings of 15th Southern Water Resources and Pollution Control Conference, Raleigh, North Carolina, pp. 63-80, April, 1966.

DESCRIPTORS

OBJECTIVE

The purpose of this investigation was to use linear programming to set production rates and waste treatment plant investment in such a way as to maximize mill profits while meeting stream dissolved oxygen standards.

MODEL/METHOD

Stream oxygen standards were converted to maximum allowable BOD discharge using the Thomas formulation for oxygen sag.

An objective function for the present discounted value of net mill profits (difference between production times profit per unit and cost of treatment plant investment plus operations) was established as an exponential function of production and treatment capacity and then linearized in the range of 50,000-100,000 lbs/day of products. With linearized profits and assuring linear waste load vs. production rate plus constant BOD removal efficiency up to the treatment plant capacity, it becomes possible to use the standard simplex tableau method of linear programming (manual solution).

The linear program constraints were:

1) Production per day between 50,000 and 100,000 pounds of goods.
2) Plant effluent equals treated effluent plus bypass effluent.
3) Plant effluent equals constant times production rate.
4) Bypass effluent load plus treated effluent load cannot exceed allowable BOD limit.

FACTORS INCLUDED

Oxygen sag in stream plus allowable BOD load, nonlinear treatment plant costs vs. capacity, possibility of treatment bypass.

ASSUMPTIONS MADE

1) Constant profit per product unit at any production rate.
2) Constant BOD removal efficiency independently of treatment plant capacity
3) BOD represents only significant pollutant in textile plant effluent that potentially violates stream standards and affects treatment plant capacity/costs.

KEY DATA REQUIRED

1) Process flow, BOD load and profit per unit of production
2) Cost vs. capacity of treatment plant at constant removal efficiency.
3) Oxygen sag equation for stream or maximum allowable BOD

RESULTS/COMMENTS

For the simple cost and waste relationships assumed, the model permits the determination of (a) the optimum production level, and (b) the equivalent value (shadow prices) of inplant housekeeping pollution abatement practices, reductions in stream standards, etc. Limitations are the rarely achieved linearity of profit and waste load with production as well as constant BOD removal efficiency vs. capacity. The model does not deal with multiple pollution components.

Eliassen, R. and Tchobanoglous, G., "Removal of Nitrogen and Phosphorus", Proceedings of the 23rd Industrial Waste Conference, 1968, Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

The purpose of this paper is to present and discuss unit operations and processes which are applicable to the removal of nitrogen and phosphorus compounds from wastewaters in order to avoid stimulating the undesirable growth of algae and aquatic plants.

MODEL/METHOD

Important forms of nitrogen in wastewater are ammonia, nitrites and nitrates. Phosphorus compounds of importance include organic phosphorus and soluble inorganic phosphates.

Nitrogen and phosphorus removal methods may be classified as biological, chemical and physical. Removal methods for nitrogen compounds include ammonia stripping (80-98% removal efficiency), biological treatment (30-50%), anaerobic dentrification (60-95%), algae harvesting (50-90%), ion exchange (80-92%), electrochemical treatment (80-85%), electrodialysis (30-50%), reverse osmosis (65-95%), distillation (90-98%), and land application. For phosphorus, the major methods are biological treatment (10-30%), chemical precipitation (88-95%), sorbtion (90-98%), ion exchange (86-98%), modified activated sludge (60-80%),electrochemical (81-85%). Also the cost range per volume treated for each process was given as well as the cost and type of process waste to be disposed, a highly significant cost factor.

Key factors which must be considered in planning and designing facilities for removal of nitrogen and phosphorus are:

1) The use to be made of the treated wastewater.
2) Whether compounds of one or both are to be removed.
3) The available means for disposing of the ultimate contaminants.
4) The economic feasibility of the selected process or processes.

RESULTS/COMMENTS

Results are given in the three tables of comparison of alternate removal methods.

Erickson, L.E., Ho, V.S., and Fan, L.T., "Modeling and Optimization of Step Aeration Waste Treatment Systems," Journal Water Pollution Control Federation, Vol. 40, No. 5, Part I, pp.717-732, 1968.

DESCRIPTORS

OBJECTIVE

In this study the optimization (with respect to minimizing total aeration tank volume for a fixed level of organic removal) of various step aeration waste treatment processes is investigated by considering sequences of tanks arranged in series with the possibility of introducing variable quanities of influent to each compartment or tank.

MODEL/METHOD

The discrete version of the maximum principle then is used to determine the individual tank volumes with their assigned organic loads which minimize the total required volume for such a system. First order microorganism growth and nutrient consumption kinetics are used. Complete-mixing flow and plug-flow material balance equations were used to describe the resulting concentrations at each type of aeration stage.

Four types of systems are considered: a sequence of complete-mixing aeration compartments, a sequence of plug-flow aeration compartments, a complete-mixing compartment followed by a plug-flow compartment, and a plug-flow compartment with continous distribution of feed along the length of the compartment.

FACTORS INCLUDED

Steady state microorganism growth rates and limits, nutrient concentrations, nutrient consumption rates and conversion yields.

ASSUMPTIONS MADE

1) The system is isothermal and under steady state condition (including constant flows, nutrient concentrations/compositions, microorganism population, density, diffusity and viscosity).
2) The effect of endogenous respiration is assumed negligible.
3) The nutrient conversion yield factor is constant and independent of the age of the organisms.
4) The sludge and waste streams are mixed completely and instantaneously at each point where the waste is introduced; mixing requires no additional volume over and above volume required for aeration.
5) Oxygen is sufficiently supplied for oxidation.
6) The plug-flow model assumes that there is no mixing of fluid longitudinally along the flow path.

KEY DATA REQUIRED

1) Growth rate of sludge microorganisms vs. nutrient concentration (linearized) for the specific sludge and waste considered.

2) Nutrient consumption rate and conversion yield

3) Influent and effluent nutrient concentrations

RESULTS/COMMENTS

The minimum total volume and optimum load allocation for each stage for a specific degree of treatment in each of the four examined systems was presented. Using non-dimensionalized inputs, the findings are:

1) A plug-flow system with continuous feed allocation along it minimizes the required volume for the step aeration system (54% of volume of single stage completely-mixed flow aeration);

2) Single stage plug-flow requires 63% of completely-mixed flow single stage volume and is equivalent to 5 stage completely-mixed flow volume; two stage plug-flow requires 57% (54% is theoretical minimum) thus eliminating incentive to consider more than 2 stages.

3) Plug-flow is most beneficial at the back end of the system and complete mixing does not greatly increase the volume requirements at the front end of the aeration system (while probably increasing stability for non-steady state conditions).

The model may not identify optimum systems in a practical sense insofar as a) treatment plant cost is not linear with volume; b) plug-flow configurations are more expensive than completely-mixed flow and do not achieve zero longitudinal mixing; c) susceptibility to instabilities and input transients is not considered; d) optimal distribution of loads among stages changes with variations in influent.

Galler, W.S. and H.B. Gotaas, "Optimization Analysis for Biological Filter Design," Ann. Soc. Div. Eng., Journal of the Sanitary Engineering Division, Vol. 92, No. 1, pp. 163-182, 1966.

DESCRIPTORS

OBJECTIVE

This study presents a method for optimization design of the biological filter for a minimum total cost. For a given known stream flow and BOD, the analysis permits the selection of the number of filter, radius, depth and recirculation rate that will permit the minimum cost.

MODEL/METHOD

The problem of minimizing the sum of filter component costs subject to certain performance requirements can be adapted to a linear programming format. In the cost of the biological filter, the nonlinear process constraint equations and the nonlinear cost functional can be linearized using the cutting place method of Kelly. Once linearized, a solution is obtained by using the dual method developed by Lemke.

Four cases of filter design minimizing the costs of construction and operation were studied in detail, namely,(a) the trickling filter, (b) the trickling filter with settling basins, (c) the trickling filter with forced ventilation, and (d) maximizing the BOD removal from a liquid waste subject to a fixed investment cost.

FACTORS INCLUDED

BOD, DO deficit, filter radius, depth and recirculation rate, process nonlinearities, nonlinear cost relationships.

KEY ASSUMPTIONS

1. The labor costs involved in the operation of a sewage treatment plant are relatively constant for plants of a given capacity.

2. Maintenance costs are relatively constant for plants of a given capacity.

3. The cost of recirculation piping is a relatively small fraction of the total costs, and therefore, if the conditions for determining the piping (flow rate, length, etc) can be found from the optimization of the biological filter and the plant layout, the pipe sizing can be optimized separately with almost no effect on the overall optimization.
4. The cost of excavation is not included but can be readily included.
5. The filters are circular; however, the formulation can be adapted to other shapes.
6. Steady state process kinetics.

KEY DATA REQUIRED

Design requirements (plant influent and effluent, BOD in influent),component cost relationships.

RESULTS/COMMENTS

1. In studying optimization of trickling filter design, it was found that the depth and recirculation ratio are dependent on the BOD in the filter influent and desired BOD reduction, and are independent of the plant influent volumetric rate.
2. Variation of the cost parameters within reasonable limits does not affect the design variables when cost is being minimized.
3. For optimum design conditions, the hydraulic rate through the filter will be at the maximum level permitted until the recirculation ratio is approximately 4 to 1. After this ratio is achieved, the hydraulic rate will decrease (equation for decrease is given).
4. At recirculation ratios lower than the maximum effective limit of about four, the cost of increasing the diameter and size of the filter is greater than increasing the recirculation to obtain increased BOD removal.
5. The inclusion of settling basins does not alter the optimum design characteristics of the filter.
6. Deep filters having forced ventilation are more economical than shallow filters only for high reductions in BOD.

7. Theoretically, one filter provides optimum cost conditions; the most economical design will have the minimum number of units to provide the necessary operating flexibility.

The equations and curves presented provide optimum biological filter system designs subject to the validity of the accepted process models incorporated in the linear program.

Meier, W.L., R.W. Lawless, C.S. Beightler, "Geometric Programming: New Optimization Technique for Water Resource Analysts," Proceedings of the Fourth American Water Resources Conference, AWRA, Urbana, III., 1968.

DESCRIPTORS

OBJECTIVE

An optimization technique called "geometric programming" is demonstrated for application to water resource analysis, particularly engineering design optimization. Basic theory and formal proofs are not considered in the paper.

MODEL/METHOD

Geometric programming is a recent algorithmic method for solving non-linear mathematical programming problems (e.g., function to be maximized or minimized subject to constraints) with non-linear objective functions and/ or constraints.

The technique of geometric programming is illustrated by two examples. In the first example, the objective function is to find the optimal dimensions of a cylindrical storage tank that would minimize the costs of construction of the tank and its operation as a storage reservoir. A non-linear cost equation of three non-linear terms is developed which includes tank dimensions, total volume to be supplied from storage per unit of time, and cost coefficients which are related to the costs of filling the tank, material for the base, and material for the sides.

Any generalized polynomial (termed posynomial) with positive real coefficients and real exponents is suitable. Partial derivatives are taken with respect to the values to be optimized. A change of variable based on duality theory is introduced so that three optimum weights are defined as the portion of the total cost attributed to each term of the posynomial. Using the fact that the sum of the weights must equal one, and simplification of the partial derivative equations yields 3 simultaneous linear equations in the 3 weights from which a solution of optimum weights independent of the cost coefficients is derived. The distribution of costs thus obtained remains invariant regardless of the values of the cost coefficients, an important unique feature of the algorithm. Further substitution of the optimum weights yields minimum cost values in terms of the original cost coefficients and constants.

In the second example, an additional term is added to the original cost posynomial, adding an additional optimum weight. This additional weight gives an underdetermined system of 3 linear equations in 4 weights, therefore all weights are expressed in terms of one of the weights. A "substituted dual function" is developed by substituting these expressions for the weights (in terms of the single "representing weight") into the objective function. It has been proved in geometric programming theory that when the substituted dual function is maximized this maximum value is equal to the minimum cost. The optimum value of the representing weight is found by obtaining the first derivative of the logarithm of the substituted dual function, setting it to zero, and solving. The remaining minimizing variables can be obtained following procedures given in the first example.

The number of weight terms minus the number of linear equations in the weights is termed "degree of difficulty" (first example had zero, second had one).

Both examples are free of physical constraints. Such constraints, if they occur, are handled in geometric programming procedures by defining additional weights and augmenting the dual function with terms generated by the constraints.

RESULTS/COMMENTS

The geometric programming technique is in its infancy. Use of the technique permits direct solution of a large class of non-linear optimization problems in engineering design and basin optimization which heretofore had to be solved by approximation techniques. However, it appears that very few problems of degree of difficulty more than one are computationally tractable, a serious limitation of the algorithm. An IBM 360/65 FORTRAN program has been written.

SIMILAR/RELATED REFERENCES

1. Duffin, R.J., E.L. Peterson, and C.M. Zener, Geometric Programming, John Wilder and Sons, Inc., New York, 1967.

Parker, D.S., J.R. Monser, R.G. Spicher, "Unit Process Performance Modeling and Economics for Cannery Waste Treatment," Resources Engineers, Inc., Walnut Creek, California. In: Proceedings of the 23rd Industrial Waste Conference, 1968. Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

Individual treatment and process models are formulated to determine which processes are "best" and at what level of removal each of the alternative processes should be operated to minimize cost of the entire treatment for a specific cannery's wastes. Details are given for 6 out of the 16 processes considered.

MODEL/METHOD

For each process there are essentially two analyses:

a. A deterministic engineering "performance model" relating process removal efficiency and the equipment/operational parameters that affect efficiency is formulated based on available design and experience data. Capital, operating and land costs are then estimated as a function of the equipment/operational parameters.

b. Straightforward minimization or search techniques are then used to establish minimum cost combinations of equipment/operating parameters for each total flow/removal efficiency combination. This is the cost-size-efficiency (C-S-E) relationship for each process.

For simplicity, a set of second order polynomial fits (one each for capital costs, operations and land) to the C-S-E relationships for each of 12 treatment processes was established and tabulated. The resulting data fits generally had correlation coefficients greater than 0.98.

Processes for which C-S-E relations are given are:

1. Screen
2. Sedimentation
3. Chemical precipitation
4. Chemical oxidation
5. Trickling filter
6. Activated sludge
7. Aerated lagoons
8. Anaerobic ponds
9. Facultative ponds
10. Aerobic pond
11. Spray irrigation
12. Evaporation and percolation

ASSUMPTIONS MADE:

1. Activated sludge: first-order, steady state kinetics and COD removal proportional to BOD removal are assumed.

2. Ponds: regression fits for existing ponds using only areal waste loading and detention time give adequate prediction of efficiency.

3. Chemical oxidation: laboratory-scale chemical oxidation removal efficiencies will apply to full-scale processes.

4. Second order polynomials are adequate fits for all C-S-E relationships.

Pearson, E.A., "Kinetics of Biological Treatment," Special Lectures Series: Advances in Water Quality Improvement, University of Texas, Austin, April 6, 1966.

DESCRIPTORS

OBJECTIVE

The objectives of this paper are:

1. To present a consistent and rational basis for kinetic modeling of biological waste treatment processes.

2. To indicate, demonstrate and emphasize the value of kinetic modeling in process evaluation and in the analytical comparison of different biological processes (viz, aerobic and anaerobic).

MODEL/METHOD

A unified kinetic description of both aerobic and anaerobic waste treatment systems in the absence of inhibitory effects is presented. The kinetic model for growth and substrate removal is based upon that of Michaelis-Menten (linear cell growth rate and substrate removal rate including a linear cell decay term constitute the basic kinetic descriptions of the process). Basic steady state relations for influent load, residence time, effluent quality and cell recycling are presented. In addition, operating conditions for maximizing cell production (i.e., maximizing P or N removal in the form of cellular material) are desired; these conditions are quite different from maximum BOD removal.

The need for additional laboratory and field determination of the applicable kinetic constants is emphasized. Most of the currently available data on aerobic and anaerobic process constants are presented in tabular form.

FACTORS INCLUDED

Steady-state first order bacterial growth and substrate (BOD or COD) removal, cell decay, cell recycling, reactor volumes and hydraulic retention times.

ASSUMPTIONS MADE

1. For Michaelis-Menten model:
    a. The enzyme plus the enzyme-substrate complex is proportional to the total "active solids" concentration.

    b. The growth rate is proportional to the enzyme substrate complex concentration.

2. For the process material balance:
    a. The process is at steady state; no inhibition effects occur at any load/growth rate combinations.

    b. The reactor volume includes the volume of the cell separator; both the separator volume and the cell mass in the separator are negligible (true only for laboratory studies).

    c. The wastage of cells (net growth) is equal to the cell concentration in the effluent stream times the flow rate.

DATA REQUIRED

The following microbiological kinetic constants of aerobic and anaerobic treatment systems are required:

1. Substrate concentration at one half maximum growth rate; maximum growth rate.

2. Flow, load and cell mass leaving and entering reactor; reactor volume.

3. Yield coefficient; endogenous respiration rate (decay); oxygen requirement constants for oxidized cells and for substrate removed.

RESULTS/COMMENTS

If aerobic and anaerobic processes are to be evaluated for a specific waste treatment problem on a rational economic feasibility basis, the development of accurate kinetic constants for both processes is an absolute requirement. Unfortunately the data used here were obtained from laboratory studies. Additional studies of full scale plants are needed to develop more reliable estimates of treatment kinetics, particularly for anaerobic systems.

This approach does not address transients due to variable flows, loads or start up nor does it address inhibitory effects; both considerations are important in addressing process stability.

SIMILAR/RELATED REFERENCES

1. Stewart, M.J., Reaction Kinetics and Operational Parameters of Continuous Flow Anaerobic Fermentation Processes. Sanitary Engineering Research Laboratory Publication No. 4 IER Series 90; Berkley, University of California (June 1958).

Smith, R., "Preliminary Design of Wastewater Treatment Systems," Proceedings, American Society of Civil Engineers - Journal of the Sanitary Division, Vol. 95, No. SAI, pp. 117-145, Feb., 1969.

DESCRIPTORS

OBJECTIVE

Purpose of this paper is to bring together in one computational scheme the significant cost and performance relationships for a group of wastewater treatment processes (arranged in a single typical configuration for domestic sewage treatment) and to attempt to calculate the performance and cost of the system as a whole based on relationships which have been developed for the processes individually.

MODEL/METHOD

A separate model is adapted for each individual process, which describes the relationship of equipment engineering parameters to process performance variables. The resulting engineering parameters are used to compute the unit process capital costs and operating costs using full size plant compilations by Russell and by Swanson. Domestic wastes are characterized in the models by 10 categories: biodegradable carbon, non-degradable carbon, N, P, and inorganic fixed matter (dissolved and solid for each). The unit processes described are: (a) primary settler, described by a linear model with two parameters; (b) aerator and final settler, steady-state kinetics (Eckenfelder) are used (c) nitrification in the aerator, steady-state kinetics for the Nitrosomonas material describe balance; (d) the thickener, with performance described linearly by two parameters (solids recovery ratio and the total solids in the underflow stream); (e) digester, exponential relationships were used to describe the digester (McCarthy); (f) sludge elutriation, the single-stage washing step is specified by the solids recovery ratio and the concentration of solids at a given station; (g) vacuum filtration and sludge drying beds, described by McCarthy's empirical relationship between the concentration of solids at a given station; (h) vacuum filtration and sludge drying beds, described by McCarthy's empirical relationship between the concentration of sludge entering the vacuum filter and the moisture content of the filtered sludge; (j) sludge incineration, the total cost of sludge incinerated per year is given; (k) disinfection, standard engineering procedure was used (chlorine contact tank).

Sample costs (capital, total cost per 1000 gallons treated and process costs) have been computed for plants from 1-100 MGD capacity and 8-40 ppm of effluent BOD.

FACTORS INCLUDED

Steady state activated sludge kinetics, limiting conditions for nitrification processes, temperature sensitivity of bacterial processes, distinction between biodegradable and non-degradable carbon as well as dissolved vs. solid BOD.

ASSUMPTIONS

1. PRIMARY SETTLER:
    - a. All classes of suspended solids in primary settler are treated with the same efficiency (same for final settler).
2. AERATOR AND FINAL SETTLER:
    - a. In achieving the effluent BOD all of the soluble food is used first.
    - b. Steady-state conditions hold and waste composition has constant average properties of domestic waste (fixed proportions of nitrogen, phosphorus, solids, etc.).
3. NITRIFICATION IN THE AERATOR:
    - a. Organic nitrogen required for new sludge is assumed equal to organic nitrogen available from nutrients under nitrifying conditions; therefore the ammonia to be oxidized is assumed equal to the influent ammonia.
    - b. Sufficient oxygen for substaining nitrification is supplied and no inhibitory substances are present; 99% of ammonia is converted to nitrate if nitrifying conditions are met.
    - c. Each element of water moves down the aeration tank without mixing; steady state nitrification kinetics hold with constants as given by Downing.
4. AIR REQUIREMENTS:
    - a. When the detention time to achieve nitrification is less than or equal to the detention time required for BOD removal, it is assumed that sufficient oxygen must be supplied to convert ammonia to nitrate.

5. DIGESTER:

   a. Anaerobic steady state laboratory kinetics and laboratory constants hold.
   b. Organic nitrogen decomposition occurs at 65% of organic carbon rates.

6. VACUUM FILTRATION AND SLUDGE DRYING BEDS:

   a. Dissolved species at stations 16 and 15 are equal.

KEY DATA REQUIRED

Plant design capacity, influent BOD load, effluent BOD desired primary and final settler performance, mixed liquor suspended solids concentration in aerator, digester detention time.

RESULTS

With a fair degree of reliability the program computes the capital cost, amortization or debt service cost, and operating and maintenance cost of the entire plant (or of individual processes or groups of processes) for conventionally arranged secondary treatment plants of the type modeled. No attempt is made to optimize or to account for influent variability.

SIMILAR/RELATED REFERENCES

1. Smith, R., "Operations Research Activities at Cincinnati Water Research Laboratory," Proceedings, American Water Resources Assn., Symposium on the Analysis of Water Resources Systems (1968).

2. Smith, R., "Cost of conventional and advanced treatment of waste water," Journal WPCF, Vol. 40, No. 9, pp. 1546-1577, September, 1968.

SECTION D

HYDROLOGICAL MODELS FOR APPLICATION TO SYSTEMS ANALYSES OF WATER QUALITY-ABSTRACTED PAPERS

Author and Title	Page
Benson, M.A., and Matalas, N.C., "Synthetic Hydrology Based on Regional Statistical Parameters"	D-2
Betson, R.P., Tucker, R.L., and Haller, F.M., "Using Analytical Methods to Develop a Surface-Runoff Model"	D-4
Garrison, J.M., et. al., "Unsteady Flow Simulation in Rivers and Reservoirs"	D-6
Huggins, L. and Monke, E., "A Mathematical Model for Simulating the Hydrologic Response to a Watershed"	D-8
Payne, Kip, Neuman, W.R., and Kerri, K.D., "Daily Streamflow Simulation"	D-10
Vemuri, R. and Karplus, W., "Identification of Nonlinear Parameters of Groundwater Basins by Hybrid Computation"	D-12

Benson, M.A., and N.C. Matalas, "Synthetic Hydrology Based on Regional Statistical Parameters," Water REsources Research, Vol. 3, No. 4, 1967, pp. 931-935.

DESCRIPTORS

OBJECTIVE

Purpose of this report is to propose a method that corrects the space and time deficiencies in the procedure for synthesizing long hydrologic series for design and planning purposes.

MODEL/METHOD

This method is an extension of the Harvard "synthetic hydrology" methodology, e.g., fitting of means, standard deviations, skewness and first order serial correlations to log-transformed monthly and annual single station stream flow series in order to establish distribution characteristics for computer generation of long artifical sequences.

The extension involves multiple regression of individual station means and standard deviations against six statistically selected basin and climatological variables, (e.g., drainage area, percent forested, percent surface storage area, annual precipitation, annual snowfall, and slope of main channel). Skewness and serial correlation were found to have poor relationships with these six variables, therefore, they are given standard monthly values for an entire region. The form of the regression function is multiplicative with unknown exponents (e.g., linear equation in logarithms). Relating stream flow statistical parameters to regional climatological and basin variables allows use of all long-term records in an area, thus reducing spatial and temporal sampling errors involved in single station statistical fits. Furthermore, given the six parameter values for an ungaged location, synthetic stream flows can be generated despite the absence of historical records. Actual fitted relationships for the Potomac basin are presented.

FACTORS INCLUDED

Drainage basin characteristics, climatological factors (monthly and annual)

KEY ASSUMPTIONS MADE

1. The statistical model underlying the synthetic hydrology method is an adequate description of single station flows.
2. The multiplicative function of the six basin/climatological variables is an adequate description of their relation to mean and standard deviation of individual station flows.

KEY DATA REQUIRED

Long term stream flow records at locations throughout a given region plus values of the six basin/climatological variables for each location.

RESULTS/COMMENTS

The method was applied to Potomac River Basin data. Standard prediction error for monthly mean flows was 8-24%; for monthly standard deviations, prediction error was 19-45%. The coefficients of the regressions against basin/climatological variables show somewhat erratic monthly trends which leave the validity of the regression function and selected variables in some doubt. Nevertheless, the present method is one of the few available for generating synthetic flows for ungaged locations.

Betson, R.P., Tucker, R.L., and Haller, F.M., "Using Analytical Methods to Develop a Surface-Runoff Model", Water Resources Research, Vol. 5, No. 19, Feb. 1969.

DESCRIPTORS

OBJECTIVE

By using analytical methods, successive restrictions were imposed on a mathematical version of the U.S. Weather Bureau's graphical surface-runoff model to develop a simplified analytical model that expresses the API (antecedent precipitation index)--runoff relations. The objectives set for the model were rationality, model conciseness, goodness of fit and coefficient consistency.

MODEL/METHOD

An analytical fitting technique (TVA, 1967) was used for the simplification process; it determines an optimal set of coefficient values associated with a minimal sum of squares of the prediction error.

The mathematical API model developed by the U.S. Weather Bureau retains the concept of the season quadrant, i.e., a set of functions relating runoff index (RI) to antecedent precipitation for each week of the year. In the Weather Bureau model all these functions lie between two extreme curves describing summer (low runoff) and winter (high runoff). The SI (season index, a function of week number) interpolates between two extreme curves to determine R.I. for a given storm a given week. In the Weather Bureau formulation, 28 coefficients are required for the extreme curve plus interpolation function fit; this was simplified to one exponential equation with five coefficients expressing RI as a function of API. The surface runoff quadrant relations (surface runoff, SRO, as a function of RI) of the coaxial-method were replaced by a single polynomial function of storm rainfall (RF) and RI with one coefficient to be fitted.

The resultant analytical model expresses API-runoff relations with two equations and five coefficients.

FACTORS INCLUDED

Surface runoff, rainfall, antecedent precipitation by watershed and by week of the year.

ASSUMPTIONS MADE

The API measure coupled with week number, is a reasonable indicator of antecedent moisture conditions.

Historically fitted SRO vs. API/week number relationship adequately encompass all factors involved in individual sub-basin runoff.

KEY DATA REQUIRED

Historical API, RF, SRO records.

RESULTS/COMMENTS

When tested, runoff relations, derived with the analytical model over selected watersheds, predicted surface runoff from those watersheds somewhat better than the regional graphical relations developed for the Tennessee Valley.

The model coefficients are sensitive to watershed characteristics. The concise relations of the simplified analytical model can be rapidly derived from a historical storm list by computer. Therefore it becomes economically feasible to derive runoff vs. storm relationships for individual watersheds whose storms are not adequately predicted by the regional relations currently used.

Garrison, J.M., et. al., "Unsteady Flow Simulation in Rivers and Reservoirs," Am. Soc. Civ. Eng., Journal of the Hydraulics Division, Vol. 95, No. 5, pp.1559-1576, Sept., 1969.

DESCRIPTORS

OBJECTIVE

The purpose of this report is to develop a mathematical model for unsteady flow simulation in rivers and reservoirs, including effects such as flow reversals, wave travel, flood phenomena, etc.

MODEL/METHOD

The basic model described here involves the solution of two linear, first order, first degree partial differential equations with two independent variables (longitudinal direction, x, and time) and two unknowns (water surface elevation and mean velocity). These two equations of unsteady one-dimensional stream flow are the continuity equation and the equation of motion (lateral inflows and variation in channel cross-section in the x direction are included). Although no closed form solution exists, these can be solved numerically by writing them in finite difference form for digital computer manipulation. The advantages of computation with a fixed rather than variable net of discrete solution points are retained by using Stoker's[1] centered difference scheme to compute transient flows (spacing of .3-2.3 miles and 18-180 seconds). The boundary conditions are given (using computer tables) as discharge vs. time, water-surface elevation vs. time, or as a stage-discharge relationships. For initial conditions a steady-flow profile, a flat pool-zero flow profile a transient flow profile from previous computations may be used. From properly calibrating the appropriate model for a particular river or reservoir channel,cross sections, slopes and hydraulic resistance, time variations in stage, velocity, and water flow can be accurately predicted at any desired location along the channel from prescribed flow conditions at each end of the channel and prescribed tributary or distributed lateral inflows (or withdrawals). Other models have been developed to complement and extend the basic model and to handle special flow situations.

FACTORS INCLUDED

Local and distributed inflows and withdrawals , varying hydraulic resistance, and varying channel geometry.

ASSUMPTIONS MADE

One dimensional characteristics are assumed (e.g., depth and velocity vary only in the longitudinal direction and with time).

KEY DATA REQUIRED

Local and distributed inflows, channel geometry, hydraulic resistance, time-varying boundary conditions.

RESULTS/COMMENTS

This model has been applied to five specific TVA site studies; three were used to directly verify model accuracies of .1 to .3 feet in stage and almost perfect reproduction of transient event timing after model calibration. (Velocity verification was poorer due to difficulty of comparing the mean velocities modeled vs. actual in-channel measurements). Important uses of the model are:

1) To guide timing and location of measurement effort for transient phenomena and basic resistance coefficients.

2) For water quality modeling and measurement the model can show the actual movement of a mass of water in a flow system, giving accurate definitions of decay times, uptake times, exposure times, etc., regardless of the system unsteadiness.

3) To select the best locations for future power plant sites on the basis of the most desirable flow conditions, including critical transient phenomena.

4) To regulate stream reservoir system flows including control of transient effects.

5) To route large flows through a reservoir or river reach based on accurate predictions of staged and flows vs. location and time.

6) To study dam failure problems.

The following limitations of the mathmatical model have been found:

1) Stability and convergence of the computation scheme depending on the computation net used.

2) Supercritical flows cannot be calculated.

3) Bores cannot be computed.

4) Branching flows or complex system flows can only be computed by successive applications of the model for each branch.

5) Stratified flows cannot be computed with the model described herein.

6) Distortion of wave speed occurs in regions where rapid changes occur between computation net points.

7) Extensive and relatively accurate field measurements of both basic channel properties and observed transient flows are necessary to calibrate the model.

8) Fairly high computer time expenditures are involved (e.g. 2-7 min. of IBM 360 time per day of simulation).

Huggins, L. and Monke, E., "A Mathematical Model for Simulating the Hydrologic Response to a Watershed," Water Resources Research, Vol. 4, No. 3, 1968, pp.529-539.

DESCRIPTORS

OBJECTIVE

A generalized mathematical model is developed to simulate, e.g.the surface runoff from watersheds.

MODEL/METHOD

The model avoids the use of lumped parameters by delineating the watershed as a grid of small, independent elements. The element must be of sufficiently small size so that all hydrologically significant parameters e.g. slope steepness and direction, vegetation, rainfall and infiltration rates, etc. are uniform within the boundaries of each element. The composite run-off hydrograph from the entire watershed is assuming a model for the runoff hydrograph for each element and applying the equation of continuity to integrate the responses from all elements.

This model was applied to two small watersheds.

FACTORS INCLUDED

Slope steepness and direction, vegetation, rainfall infiltration rates, rate of surface runoff, rate of evaporation, drainage rate, porosity of the soil, soil moisture, depth of flow for each grid element of the watershed.

ASSUMPTIONS MADE

1) The entire watershed is composed of a composite group of essentially independent internally uniform elements.

2) At every point within the watershed a functional relationship exists between the rate of surface runoff (dependent variable) and the hydrologic parameters of soil properties, topography, vegetation, temperature, time and rainfall from the beginning of the storm event and the depth of flow.

3) That the rate which water was intercepted before satisfying the interception storage could be computed as the percentage of the total area covered by the horizontal projected leaf surfaces times the rainfall rate.

4) Holtan's empirical infiltration equation was assumed. Measurements of constants were based on: (a) the drainage rate was assumed to be equal to the infiltration rate as required by continuity considerations when the soil was saturated, (b) the drainage rate was taken to be zero when the soil moisture content was less than field capacity,

(c) an arbitary polynomial relation was used to calculate the drainage rate with respect to unsaturated pore volume when the soil water content was between field capacity and saturation.

5) The typical soils of the area being studied are such that interflow was assumed to be negligible.

6) For surface runoff, the hydraulic gradient in Manning's equation was assumed to be equal to the slope of the element and the hydraulic radius was assumed to be equal to the average depth of water in excess of the surface retention within the element.

KEY DATA REQUIRED

Quantitative measurement (of all factors included previously) for each grid element.

RESULTS/COMMENTS

Application of this model to two small experimental watersheds (25' square grid elements) indicated a need for additional research to define better the relationships for surface runoff and infiltration to improve the reliability of the simulated runoff hydrographs.

A general purpose Fortran 4 program to implement the watershed model for arbitrary watershed conditions is available (Huggins and Monke, 1966).

The model has the following advantages:

1) An ability to readily simulate watershed conditions and both spatial and temporal storm distributions.

2) Elimination of the requirement for lumped parameter coefficients that must represent 'effective averages' for a spatially varied parameter.

3) Independence between the basic model formulation and the relationship chosen to model each of the component hydrologic processes.

4) Subdivision of the model into small elements facilities independent study of the component parts and a resultant improvement in model accuracy.

Current major weaknesses are the imprecise empirical nature of the assumed infiltration and surface runoff relationships plus inadequate descriptions of antecedent soil moisture.

Payne, Kip, Neuman, W.R., and Kerri, K.D., "Daily Streamflow Simulation," Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, pp. 1165, HY4, July 1969.

DESCRIPTORS

OBJECTIVE

The objective is to develop a multiple-station daily streamflow generator capable of simulating daily flow sequences with frequency characteristics similar to those of the historical records.

MODEL/METHOD

The present simulator is an extension of the monthly simulator developed by Beard, but differs from Beard's second order Markovian single station daily simulator in two respects: (1) Historical hydrographs are rearranged; and (2) Simulation of monthly flows to adjust daily flows is not necessary.

The hydrographs within each month are rearranged around critical hydrologic events (peak and minimum flow days) to preserve the ascension and recession curve behavior. The Log-Pearson Type III method was used to transform the rearranged flows to normal distributions and to determine regression coefficients between stations and days. A chi-squared goodness of fit test was used to test for the normality of the transformed flows. Flows are simulated by transforming generated random numbers on the basis of the statistical parameters computed from the rearranged daily flows. The adequacy of the technique is tested by comparing the frequency distributions of the important statistical properties of the historical flows (distributions of annual means, maximum and minimum daily, maximum 3-day average, minimum 7-day average flow, etc.) with those of the simulated flows for two gaging stations on the Calapooia River in Oregon. To reduce the excess variation that the minimum and maximum simulated daily flows exhibited, two empirical dampening constants were introduced into the simulator.

FACTORS INCLUDED

Daily streamflow, multiple station correlations, monthly peaks with ascension and recession behavior.

ASSUMPTIONS MADE

Hydrograph rearrangement does not affect time series behavior; Log-Pearson Type III transformation and regression method applied monthly preserves essential statistics.

KEY DATA REQUIRED

Sufficient station-years of daily hydrographs.

RESULTS/COMMENTS

The proposed simulator is capable of generating both nonhistorical flow sequences with statistical properties and hydrographs similar to historical flows. Therefore it can be used to analyze the response of proposed and existing water resources systems to potential nonhistorical flow sequences of longer duration than historical records. Empirical judgment is required in rearranging daily hydrographs and selecting dampening constants. The model demonstrated reasonable extreme value statistical behavior using the flow records of the two gaging station selected.

Vemuri, R. and Karplus, W., "Identification of Nonlinear Parameters of Groundwater Basins by Hybrid Computation," Water Resources Research, Vol. 5, No. 1, pp. 172-185, 1969.

DESCRIPTORS

OBJECTIVE

The purpose of this report is to identify the parameter (transmissibility, storage coefficient and the boundary) of an unconfined aquifer.

MODEL/METHOD

Identification of parameters of an unconfined aquifer in which the dynamics of the water table are describable by a partial differential equation are looked upon as a control system problem in distributed parameter systems.

Using a maximum priciple in conjunction with a steepest descent algorithm, the transmissibility of an aquifer is identified, starting from observed values of input-output as data. This algorithmic procedure is blended with a heuristic empirical method to identify the storage coefficient and the boundary of an aquifer. This was done by taking full advantage of the flexibility offered by the computer via the analog patch board. Results of computations carried out on a hybrid computer (digital computer plus passive resistance network) are presented.

FACTORS INCLUDED

Locally varying transmissibility, boundaries and storage coefficients of the aquifer.

ASSUMPTIONS MADE

1) Hybrid identification is achieved by assuming a nominal shape to the boundary of the aquifer and a nominal set of values to the storage coefficients.
2) A ground-water flow field is characterized by a quasilinear partial differential equation piecewise linear in the time domain. (Vemuri and Dracup, 1967).
3) The transmissibility of the aquifer and the storage coefficient are only functions of spatial coordinates and independent of the water elevation level during each time subinterval.
4) Assuming that the aquifer is bounded on all sides by vertical imaginary impermeable barriers it follows that the boundary of the aquifer is not a function of the water elevation level.

KEY DATA REQUIRED

Historical water elevation level and water flow at points expressed in a Cartesian system plus precipitation inflow, artificial recharge and pumpage.

RESULTS/COMMENTS

The technique was applied to study the San Fernando Valley basin in the City of Los Angeles and some typical results for transmissibility contours, storage coefficient contours and for the boundary of the aquifer are presented in graphs.

- transmissibilities and storage coefficients tend to decrease with declining water tables.
- the shape of the boundary that gives the best model can be seen from the shape of the resistance network on the analog patch board.

SECTION E

STUDIES AND MODELS OF OXYGEN BALANCE IN STREAMS - ABSTRACTED PAPERS

Author and Title | Page

1. Churchill, M.A., Elmore, H.L. and Buckingham, R.A., "The Prediction of Stream Aeration Rates," E-2
2. Ignjatovic, Lasar, R. "Effect of Photosynthesis on Oxygen Saturation," E-4
3. Isaacs, W.P. and Maag, J.A., "Investigation of the Effects of Channel Geometry and Surface Velocity on the Reaeration Coefficient," E-6
4. Kartchner, A.D., N. Dixon, & D.W. Hendricks, "Modeling Diurnal Fluctuations in Stream Temperature and Dissolved Oxygen," E-8
5. Li, W., "Unsteady Dissolved - Oxygen Sag in a Stream," E-10
6. McKeown, James J., "Studies on In-Stream Aeration," E-12
7. Merritt, C.A., D.B. McDonald, W. L. Paulson, "The Effect of Photosynthesis on the Oxygen Balance in a Midwestern Stream," E-13
8. O'Connor, D.J., "The Temporal and Spatial Distribution of Dissolved Oxygen in Streams," E-15
9. Thayer, R., and R.G. Krutchkoff, "Stochastic Model for BOD and DO in Streams," E-18

Churchill, M.A., Elmore, H.L. and Buckingham, R.A., "The Prediction of Stream Aeration Rates," Journal of the Sanitary Engineering Division ASCE, Vol. 88, No. SA4, pp. 1-46, 1962.

DESCRIPTORS

OBJECTIVE

The purpose of this investigation is to develop a fundamental formula based on field measurnents for predicting the reaeration rate (K_2) of natural stream channels (non-stratified, non-"white water," free of organic pollution) as a function of the hydraulic properties of the channels.

MODEL/METHOD

Reaches for this study were selected to fulfill the following requirements: a) location downstream from a deep reservoir so that water released is low in DO (and essentially free of BOD) during some summer and fall period and close enough to the reservoir so as to be unsaturated; b) relatively uniform hydraulic properties and essentially no benthic organic pollution; c) wide range of flow, velocity and depth. Flows were held steady for approximately 24 hour periods during the study at the upstream hydroplants. DO samples for each end of each reach were taken at 7 positions across the stream hourly. The laboratory analysis and research included new measurements of DO saturation concentrations, effect of temperature on reaeration rate, and oxygen contribution of indigenous aquatic plants to correct raw DO readings from streams. From the above results K_2's were calculated based on the linear differential equation for reaeration rate proportional to oxygen deficit. 509 geometric means of K_2 values for each steady state measurement period on each reach were fitted (multiple regression least squares) to 19 different equations in 9 variables (velocity, mean depth, energy slope, resistance coefficient, density, viscosity, surface tension, molecular diffusion and vertical diffusion coefficient). The equations tested were based on dimensional analysis. Goodness of fit was measured using the multiple correlation coefficient.

FACTORS INCLUDED

DO variation with time and cross-channel position for each reach; bay hydraulic properties of channels; correction and/or checks for : BOD, plankton and benthic photosynthesis, mineral and temperature effects.

KEY DATA REQUIRED

Channel geometry and hydraulic parameters, flow velocity, hourly DO measurements, temperature, laboratory determinations of pollutant effect on reaeration rate.

RESULTS/COMMENTS

1) 19 dimensionally correct exponential-multiplicative equations in the 9 key hydraulic variables were fitted to predict K_2 over the range of reaches: all equations had approximately equally good fits (multiple correlations of .805-.846).

2) The simplest satisfactory equation used only powers of velocity and mean depth to predict K_2 (valid for clean water and uniform reaches in the absence of stratification and white water). No significant improvement is obtained by including more variables. Note that slope and reisitance are strongly correlated with depth in the basic sample of reaches; therefore, they exert an indirect effect through depth in the simple equation. The simple equation is accurate to ± 5% with 95% confidence at the mean of the data; at the extremes it still predicts K_2 within ± 15%.

3) The prediction equation can be applied to polluted water by adjusting K_2 by the percentage difference in clean vs. polluted water reaeration rate (laboratory impeller tests on samples of each).

4) The Streeter-Phelps equation cannot be used directly for K_2 determination (due to errors through BOD, contaminants, benthic demand. etc).

5) The O'Connor and Dobbins fits for K_2 are theoretically and empirically deficient.

6) DO sampling must take into account significant cross-stream variations (as much as 1 ppm.); vertical gradients are insignificant in unstratified stream.

7) Photosynthesis even in clean streams can leave a significant effect and must be corrected for.

8) Mineralization and pH have negligible effect of DO.

9) The reaeration rate increases with water temperature at the geometric rate of 2.41% per degree centigrade.

Large unexplained cyclic variation (2-12 hour period) as a function of time for each reach should be noted (as large as ± 100%); these are simply averaged out in the final fits. The simplest equation's accuracy may be degraded when applied to other regions due to possibly differing correlations of slope and resistance with depth as compared to the correlation for the Tennessee Valley reaches used in the data base.

Ignjatovic, Lazar R., "Effect of Photosynthesis on Oxygen Saturation," Journal Water Pollution Control Federation, Vol. 40, No. 5, Part 2, May, 1968.

DESCRIPTORS

OBJECTIVE

The goal of this paper is to prove the existence of oxygen supersaturation in a natural body of water and to search for its source.

MODEL/METHOD

Since the solubility (of O_2) is a function of temperature, pressure, and salinity these factors are discussed and evaluated within existing data for the Roanoke Rapids Reservoir in North Carolina.[1]

A hypothesis was made that supersaturation is due to photosynthesis. The method of elimination is used to test the above hypothesis. It is shown that the observed degree of supersaturation cannot be produced in a natural water body by: (a) temperature changes, (b) pressure changes, (c) vertical mixing or stratified water, (d) vertical diffusion, or (e) evaporation.

Samples of the Roanoke Rapids Reservoir were taken at 2 stations at 5- ft. depth to obtain DO, temperature patterns, turbidity and the other factors related to solubility.

Turbidity was determined by comparing a sample in a French square 200-ml bottle with the standards in the same type of bottle.

The samples which represent consecutive clear days with 80% sunshine and consecutive cloudy days with 40% or less sunshine were selected to test the hypothesis of photosynthetic oxygen production. Calculations with regard to the level of oxygen supersaturation are based on the Truesdale et. al. values for oxygen saturation.

FACTORS INCLUDED

DO, temperature, pressure, salinity, evaporation, diffusion, light intensity.

ASSUMPTIONS MADE

It is assumed that a normal biological picture exists in the reservoir water and that it is not changed appreciably during the two-month sampling period.

RESULTS/COMMENTS

1) Dissolved oxygen supersaturation was observed to be

as high as 25% at the 5-Ft. depth at an average temperature of 25°C and over 80% of possible sunshine in summer at the latitude 35 to 40 degrees N (an additional 9% per day of supersaturated oxygen was consumed by the existing natural BOD load).

2) This value of supersaturation cannot be produced by temperature changes, pressure changes, vertical mixing of stratified water, vertical diffusion, or evaporation, whether these factors act separately or together. Photosynthesis is the only force capable of producing this magnitude of supersaturation.

3) The effect of sunshine and algae on oxygen levels in streams should be recognized as having considerable significance (average DO levels for 80% or above sunshine days were 25% higher than for 40% or below sunshine). The problems associated with algae growth and death appear to be quite important in stream pollution assessment and control.

Isaacs, W.P. and Maag, J.A., "Investigation of the Effects of Channel Geometry and Surface Velocity on the Reaeration Coefficient," Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

To predict as a function of channel characteristics the reaeration rate coefficient, K_2, based on existing empirical data and theoretical considerations.

MODEL/METHOD

The authors begin by reviewing existing prediction attempts.

Adeney and Becker (1919) showed that the change in oxygen deficit was a first order kinetic reaction involving the reaeration rate constant.

W.G. Whitman and W.K. Lewis'(1923) two film theory proposing the existence of laminar layers of gas and liquid at the two phases interface made their model **impractical** due to immeasurable film thickness.

R. Higbie's idea (1935) that the constant K_2 is a function of contact-time of turbulent eddies at an interface was rejected due to indeterminacy of "contact time."

Danckwert's proposal (1951) that the constant is a function of water surface renewal rate also met the same fate due to indeterminacy of the parameters.

Streeter (1926) proposed a model (suprisingly similar to Churchill's fit in 1962) involving average stream velocity and average depth of flow controlled by constant coefficients which were never explained in terms of stream parameters.

The validity of the O'Conner and Dobbins equation involving mean stream velocity, average depth and slope was doubted due to inconsistency between prediction and actual data plus theoretical flaws.

Churchill's model (1962) based on extensive correlation analysis performed upon measured stream variables and actual data from streams although dimensionally non-homogeneous is considered the best field study. The parameters involved are the mean stream velocity, the average depth and water temperature.

Krenkel and Orlob (1962) proposed an equation(developed from collected data involving gas activation energy for molecule transfer into turbulent fluid)with absolute temperature, gas constant and longitudinal dispersion coefficient. The Whitman and Lewis film concept was combined with the Dobbins model but the evaluation technique for film replacement frequency and film thickness received much criticism.

Thackston and Krenkel (1966) definition of reaeration constant using recirulation is believed to be invalid due to the lack of similarity between flume and stream.

Owens, Edwards, and Gibbs (1964) empirical equation appears biased due to data base emphasizing streams with high K_2's.

Langbein and Durum (1967) have proposed that reaeration rate constant is a function of mean velocity, mean depth, position along the stream and the geomorphic characteristics based on Churchill's data. Churchill measured only 30 stream reaches but Langbein and Durum plotted only 24 of these reaches; no correlation coefficients were reported.

Tsivoglou's (1965) approach to the reaeration constant through the use of inert gases showed excellent comparison between reaeration coefficient and transfer rate of inert gases.

Isaacs (1967) using simulated streams defined the reaeration constant in measurable stream parameters (for rectangular cross sections). This model was fitted to Churchill's data on streams for evaluating the linear constant used in the model - 20% discrepancy was found between simulated and natural stream fits.

The present study modifies the original Isaacs fit by adding a specific non-dimensional shape factor (to account for non-rectangular stream cross section and a non-dimensional empirical factor of proportionality between mean velocity (as used by Churchill) and surface velocity (clearly important in reaeration).

KEY DATA REQUIRED

Mean velocity or preferably surface velocity, temperature, mean depth, accurate stream cross sections (for computing shape factors) and for polluted stream predictions reaeration rate percentage difference from clean water value.

RESULTS/COMMENTS

The fit obtained is significantly better than Churchill's original fit (.95 vs. .82 correlation) while at the same time offering a dimensionally homogeneous equation that also fits laboratory simulated stream data. The current model appears to be a highly satisfactory mean of predicting reaeration rate for clean streams based on their physical characteristics.

Kartchner, A.D., N. Dixon, & D. W. Hendricks, "Modeling Diurnal Fluctuations in Stream Temperature and Dissolved Oxygen," Utah Water Research Laboratory, Utah State University, Logan, Utah. In: Proceedings of the 24th Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1969

DESCRIPTORS

OBJECTIVE

Dissolved oxygen and temperature exhibit significant diurnal fluctuations which could impact upon the biotic community of streams. Use of these parameters in basic simulation models therefore requires short-time (e.g., hourly) time incrementation. This study is designed to illustrate the characteristics and possible implications of these diurnal fluctuation parameters in small, rapidly flowing streams.

MODEL/METHOD

Two alternative techniques by which short-time variations can be represented are presented: a Fourier series curve fitting approach and a time series index approach.

Both models are empirically derived and require sequences of hourly data relative to the pertinent parameters.

Models were developed by fitting and/or analyzing DO and temperature data for periods of several days to one week. The Fourier model is fitted to data utilizing least square methods. The time series analysis is performed by the ratio-to-moving average method. To ascertain the character of seasonal changes, 22 data blocks of several days each representing different times of the year are analyzed (summer data used was incomplete). Diurnal patterns of variation characteristic of each season are then developed. Diurnal indexes are based on ratios of observed hourly parameter values to seasonal data block means in the time series approach. Fourier coefficient seasonal trends are shown through fitted values for each block of data.

ASSUMPTIONS MADE

1. A two term Fourier series model can provide an adequate fit to DO and stream temperature diurnal cycles.

2. For the time series approach, the values of DO and stream temperatures have only seasonal and diurnal cyclical components.

RESULTS/COMMENTS

The authors conclude the modeling techniques presented provide a systematic method for assessing DO and temperature fluctuations, and they can be used to adjust currently available mean data which is frequently based on daytime-only sampling procedures. Either model accounts for about 90% of the DO variability and 75% of the temperature over a one week period; annual fits are considerably poorer. Weekly standard deviations are approximately .25 ppm and .67°. These models are limited by the characteristics of the data from which the model was derived. Extraneous factors, present at other locations (even in the same stream), can alter the basic data and may lead to substantially different sets of diurnal and seasonal indexes.

Unfortunately, extensive in-stream measurement records are needed for every location to be modeled. The DO extreme fluctuations about the diurnal trend are of the greatest interest in terms of effects on biota; these are not directly statistically analyzed or modeled.

Li. W., "Unsteady Dissolved - Oxygen Sag in a Stream", Journal of the Sanitary Engineering Division, ASCE, Vol. 88, No. SA3, May, 1962

DESCRIPTORS

OBJECTIVE

The paper aims at finding a solution of the distribution of dissolved oxygen at any cross section of a polluted stream in which the volume and velocity of flow are steady but not necessarily uniform at all cross sections. It also attempts to compute the unsteady distribution of DO due to unsteady initial oxygen content and BOD load along the stream.

MODEL/METHOD

The deoxygenation of polluted water and atmospheric reaeration cause variation in DO concentration with respect to time and distance. The difference in the mass inflow and outflow of oxygen and BOD causes relative changes both in oxygen content and BOD in the volume bounded by two cross sections a certain distance apart. There is a linear relationship between the BOD changes, BOD of added discharge and the residual BOD in the stream. The residual BOD is determined from the linear differential equations describing their relationship. Similarly, the dissolved oxygen deficit for the general case (varying cross section, velocity and discharge BOD/DO load) is calculated from the first order equations.

The author develops the differential equations and solutions for the following special cases:

a. Steady-state BOD and DO loading;
b. BOD discharge loading fluctuations as a function of time;
c. BOD and DO discharge loading fluctuations of one cycle per day.

ASSUMPTIONS

1. Constant stream discharge.
2. The sewage is well mixed both vertically and laterally.
3. No effect of longitudinal turbulent diffusion.
4. Deoxygenation and reaeration are linear processes.
5. Benthic and photosynthetic contributions to the oxygen balance can be excluded.

CONCLUSION

The equations predicting the DO/BOD balance are useful generalized solutions, given the simplifications inherent in the linear rate assumptions for the oxygen depletion and rearation processes. The often ignored movement of the oxygen sag point with fluctuations in BOD and DO loading is clearly demonstrated.

McKeown, James J., "Studies on In-Stream Aeration," Department of Civil Engineering, Tufts University, Medford, Massachusetts. In: Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

The paper presents a discussion of field measurements of dissolved oxygen and estimates of oxygen transfer capabilities of dams and short sections of turbulence in streams due to rapid loss of elevations. The use of mechanical aeration for the purpose of increasing the DO content at critical oxygen sections of streams is also evaluated.

RESULTS/COMMENTS

Previous work involving analysis of data collected above and below numerous weirs and cascades is summarized. Existing, validated models for calculating deficit ratio (of dissolved oxygen) as a function of pollution levels, height of fall, and water temperature are summarized. No new models are derived.

New data are presented on dissolved oxygen contributions from dams and spillways. Data on the transfer efficiency (lbs. of O_2 per hr. per HP) of mechanical surface aerators is developed and presented. DO profiles resulting from various location configurations and numbers of aerators are presented. Operational scheduling patterns (i.e., on-off periods), water recycling patterns, and special horizontal flow or circulation enhancers are examined as methods of optimizing DO profiles in shallow waters. Unfortunately, cost data is not included though it is implied that in-stream aeration is often substantially more economical than equivalent effluent treatment.

Merritt, C.A., D.B. McDonald, W.L. Paulson, "The Effect of Photosynthesis on the Oxygen Balance in a Midwestern Stream," Department of Civil Engineering, University of Iowa, Iowa City, Iowa. In: Proceedings of the 23rd Industrial Waste Conference 1968, Purdue University, Lafayette, Indiana 1968

DESCRIPTORS

OBJECTIVE

The purpose of this study was to determine the oxygen contributed by planktonic photosynthesis in the Ohio River, which contains ample nutrients due to agricultural activity in the area, but almost no benthic vegetation.

MODEL/METHOD

Six 24-hour series were conducted using separately light and dark 300 ml. bottles (and 5.5 gallon plastic boxes) at depths of 0,2.5 and 4.5 feet with readings every 4 hours. DO measurement were conducted in the bottles (by Winkler method) and in the plastic boxes (at comparable times) using the oxygen probes and a micrometer; BOD measurements plus algal counts were also taken.

RESULTS/COMMENTS

When evaluating the oxygen resource of a stream, photosynthesis must be considered despite its high variability. In the present study plankton counts ranged from 3,600 to 8,900 organisms/ml. Photosynthetic oxygen production exceeded total respiration by 1. 9:1; photosynthesis provided 75% of river oxygen. Total oxygen produced by photosynthesis in a one foot wide cross-section of the river was 13.2 gm/day or 1.2 gm/sq.m./day, as opposed to 4.3 gm/day of reaeration.

Other important observations include:

1. Photosynthesis peaks in the early morning and levels off during the rest of the day with a sharp drop after twilight; respiration has a similarly non-sinusoidal rate during the night hours; 10% of full sunlight gives peak activity while more is harmful.

2. A presented plot shows a roughly exponential rise in DO with increasing plankton count to a slightly supersaturated asymptote (about 1 ppm) with a very wide scatter band.

3. Net photosynthetic oxygen contribution at 5 foot depth is approximately 0 and maximizes near the surface with a roughly linear trend in between, respiration is approximately constant with depth requiring .30 mg/l of O_2.

Unfortunately, no measurements were made to correlate results with either stream nutrients or light intensity at the sample depth.

SIMILAR/RELATED REFERENCES

1. O'Connell, R.L. and N.A. Thomas, "Effect of Benthic Algae on Stream Dissolved Oxygen," Journal of the Sanitary Engineering Division, ASCE, Vol, 91, No. SA3, June 1956, pp. 0-16

2. Hull, C.H.K., Discussion of "Effect of Benthic Algae on Stream Dissolved Oxygen," by Richard L. O'Connell and Nelson A. Thomas, Journal of the Sanitary Engineering Division, ASCE, Vol. 91 No. SA1, Feb. 1966, pp. 306-313.

3. Odum, H.T., "Primary Production in Flowing Waters," Limnology and Oceanography, Vol. 1, 1956, pp. 102-117.

O'Connor, D.J., "The Temporal and Spatial Distribution of Dissolved Oxygen in Streams," Water Resources Res., Vol. 3, No. 1, pp. 65 (1967)

DESCRIPTORS

OBJECTIVE

Purpose of this paper is to present methods of incorporating temporally and spatially varying factors in linear differential equation models for dissolved oxygen streams.

MODEL/METHOD

A general equation describing the temporal and spatial distribution of dissolved oxygen in a steady-state one dimensional river (e.g., no variation in cross-stream properties, no longitudinal mixing) is given. Commonly fitted functions expressing the variation of the freshwater flow (due to drainage area changes and/or groundwater contributions or losses) and cross sectional area are included as well as the various sources and sinks of oxygen (approximated as linear processes): natural and artificial aeration, the photosynthetic contribution, distributed and point sources of BOD, bacterial and algae respiration, carbonaceous and nitrogeneous oxidation, and benthal deposits. The system is treated as a linear in nature: therefore the individually computed oxygen demand/contribution components are simply added to determine the total oxygen deficit. The general equation is not solved; special cases are solved for linear increase in drainage area; 24 hours sinusoidal photosynthetic variations; constant, linear or expoɗential changes in cross-section; point and uniformly distributed sources of BOD, recession from peak flows, diurnal BOD load variations.

FACTORS INCLUDED

DO, BOD, natural and artificial aeration, photosynthetic contribution, bacterial and algae respiration, carbonaceous/nitrogenous oxidation, benthal deposits, time varying flows and loads.

ASSUMPTIONS MADE

1. One-dimensional flow.

2. All oxygen contributing or demanding processes are linear in time.

3. All processes depend only on BOD and DO levels; no inhibitory or stimulatory effects of toxins, P or N are modeled.

RESULTS/COMMENTS

Methods are shown for developing linear dissolved oxygen models in the many cases where temporal and spatial variations are important. Empirical validation is not included. Important observations are made on the significant magnitude and lag of nitrogenous BOD in wastes and the necessity for carefully controlled in-stream measurements (even when measuring linear rates of composite effects of multiple sinks and sources) Not addressed is the fact that the one-dimensional approach can significantly overestimate peak concentrations downstream from slug and rapidly varying discharges due to the failure to account for important longitudinal mixing effects.

SIMILAR/RELATED REFERENCES

1. Li, W., Unsteady dissolved oxygen sag in a stream, Proc. Paper 3129, J. Sanit. Eng. Div., Am. Soc. Civil Engrs., 88 (75), 1962

2. O'Connor, D.J., and D.M. DiToro, An analysis of the dissolved oxygen variation in a flowing stream, Proceedings, Special Lecture Series on Advances in Water Quality Improvement, University of Texas, Austin, Texas, April, 1966.

Rudolfs, Eillem and Heukelekian, H.,"Effect of Sunlight and Green Organisms on Re-aeration on Streams," Biology of Water Pollution, pp. 52-56, 1967.

DESCRIPTORS

OBJECTIVE

This paper reports a combined laboratory/field study of the effect of sunlight and green organisms on reaeration of running streams.

MODEL/METHOD

Data were obtained by sampling Delaware River for 24-hour periods; samples were taken in the middle and two quarter points at mid depth. For the laboratory experiments large samples were obtained from different points in the Delaware River. Some samples were exposed to light or kept in the dark in open containers with uniform depth. Others were distributed into glass-stoppered bottles, which were immersed in a water bath and the temperature regulated with hot and cold water. At frequent intervals (2 to 1-1/2 hours) the temperature and dissolved oxygen content were determined. All transfers of water were made by siphon immersed under water to avoid bubbles. Analyses were made to complete 24 hour cycle according to the standard A.P.H.A. methods.

FACTORS INCLUDED

DO, BOD, photosynthesis, algal count, light and temperature effects.

RESULTS/COMMENTS

In-stream measurements showed both strong diurnal and strong tidal effects; diurnal changes covered the range of 80-115% saturation. Laboratory experiments with river water containing green algae showed that small temperature changes had practically no effect; DO increased or decreased depending almost only upon light and darkness.

Direct sunlight produced the same DO level as diffused light. Do in water containing large quantities of blue-green and green algae could be decreased from supersaturation to 17% saturation by placing the water in darkness, and could also be increased to 282% saturation (after 4 1/2 days) by subjecting it to diffused light. Large changes in pH values (6.9 to 9.6) followed changes in oxygen saturation. Under similar conditions the oxygen dissolved could be decreased by almost half where the number of organisms were decreased by half.

Stream measurement results previously obtained for dissolved oxygen (without consideration of algae) have been interpreted as meaning far more than was actually warranted.

In stream pollutions surveys algal factors must be taken into consideration and great care must be taken in distinguishing night surveys from day samples.

Thayer, R., and R.G. Krutchkoff, "Stochastic Model for BOD and DO in Streams," Ann. Soc. Civ. Eng., Journal of the Sanitary Engineering Division, Vol. 93 No. 3, pp. 59-83, June, 1967

DESCRIPTORS

OBJECTIVE

To model the statistics of oxygen demand and dissolved oxygen simultaneously at any downstream point.

MODEL/METHOD

The model consists of the following five independent probabilities of small discrete changes in oxygen demand and dissolved oxygen concentrations in the stream:

1. The probability of a unit decrease in oxygen demand and dissolved oxygen due to bacterial action in a unit time interval is linearly proportional to the amount of oxygen demand present.
2. The probability of a dissolved oxygen unit increase in a unit time interval due to reaeration is proportional to the dissolved oxygen deficit.
3. The probability of a unit decrease in oxygen demand in a unit time interval as a result of sedimentation and stream bed absorption is proportional to total oxygen demands.
4. The probability of a unit increase in oxygen demand (due to uniformly distributed waste inputs along the stream) is proportional to a constant (input load rate).
5. The probability of a unit decrease per time interval in dissolved oxygen (due to the net effect of benthal demand, photosynthetic respiration and photosynthesis) a proportional to a constant (net deoxygenation rate).

The joint probability of any given dissolved oxygen and oxygen demand state is computed as the sum of probabilities of all the first order discrete steps leading to that state. All intervals are allowed to approach zero to yield a continuous formulation.

Means and variances vs. time for both variables are calculated from probability generating functions.

ASSUMPTIONS MADE

1. Uniform one dimensional steady flow with steady-state deoxygenation-reaeration processes.

2. Bacterial action, reaeration, sedimentation, oxygen demand inputs, benthal demand, photosynthetic respiration/photosynthesis operate on oxygen demand and dissolved oxygen linearly as stated above.

3. Other pollutants (e.g., N, P, or toxins) have no significant interaction with the oxygen balance.

4. Oxygen demand and dissolved oxygen are stochastic variables whose joint state can change due to 5 independent transit transition probabilities.

DATA REQUIRED

1. Oxygen demand (BOD, COD or TOD) and dissolved oxygen measurements from river stations for fitting sedimentation deoxygenation, reaeration and waste load input rates.

2. Travel time and flows.

RESULTS/COMMENTS

The equations for mean amounts of oxygen demand and dissolved oxygen vs. time derived from this model are identical to the Dobbins equations obtained from a deterministic differential equation approach based on the same linearity assumptions.

The key and most surprising result is that the variance of dissolved oxygen vs. time or distance increases with decreasing mean DO. This indicates the serious shortcomings of deterministic standards and using deterministic oxygen sag predictions to meet standards. Note that even if mean DO is slightly above standards at the sag point, this is precisely where variability is maximized; thus the probability of random standard violation becomes quite high.

Actual experimentation carried out under controlled conditions in polythylene waste cans with random samples of river water artifically polluted and reaerated supports the predicted increase in variability at the sag point. Likewise, stream data from the Sacramento River shows worst variability at the sag point though the data given for both cases is not adequate to verify the specific form of the variance prediction.

Computer programs for doing the necessary arithmetic are available.

SECTION F

MODELING OF THERMAL POLLUTION

Author and Title	Page
Christianson, A.G., and Tichenor, B.A., *Industrial Waste Guide on Thermal Pollution*	F-2
Stolzenbach, K.D., and Harleman, D.R.F., "An Analytic and Experimental Investigation of Surface Discharges and Heated Water"	F-4
Water Resources Engineers, Inc., *Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments*	F-8

Christianson, A.G. and Tichenor, B.A., Industrial Waste Guide on Thermal Pollution, Federal Water Pollution Control Administration, Northwest Region, Pacific Northwest Water Laboratory, Corvallis, Oregon, September, 1968

DESCRIPTORS

OBJECTIVE

The objective is to develop a practical guide providing basic orientation in the subject area of thermal pollution and, further, to identify sources of more detailed information as an aid to State, Federal, and local regulatory personnel, community and regional planners, and industrialists in making sound decisions with respect to thermal pollution.

RESULTS/COMMENTS

The study presents a comprehensive coverage of subject matter in handbook format. Each subject area covered (see factors covered below) includes brief orientation statements concerning the sources of thermal problem areas, time-projections of major problem situations, useful statistics and facts, tables and/or graphs of pertinent data, and mathematical models or equations for generating additional practical information.

The use of information and formulae contained in the guide book is illustrated by a concise summary of the steps leading to solution of two typical example problems in thermal pollution. Cross referencing to material in the book is extensive in the example solutions,and references to related research reports are included in the text.

FACTORS INCLUDED

The subject matter of the guide book is divided broadly into three parts;

1. Industrial waste and heat loads
2. Effects of thermal pollution
3. Control techniques and devices

The section on waste and heat loads summarizes information for both the electric power and manufacturing industries. Effects of thermal pollution includes physical, chemical and biological aspects of heated discharges. By far the largest and most important subcategory of this section is on biological effects which includes effects on bacteria, fish and shellfish, algae and other aquatic plants. The control techniques section delves into process changes, energy utilization, cooling devices, and heat plume behavior manipulation.

Both the attributes and the liabilities of a technical guide book are illustrated in this report. The simple, concise presentation of information is an attractive asset for engineers and other workers in the field. Generous cross-indexing throughout the book and illustrated examples enhance its usefulness.

The foreword to the guide book admits to omissions of important information in this first attempt to provide a guide for thermal pollution. Updating has apparently not been accomplished in almost three years during which considerable research activity has occured and new information has been developed in the field.

Stolzenbach, K. D., and Harleman, D. R. F., "An Analytic and Experimental Investigation of Surface Discharges of Heated Water," Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, Feb., 1971.

DESCRIPTORS

OBJECTIVE

The objective of the study is the theoretical development and experimental validation of a steady-state analytic model for computation of temperature distributions in the near field (the zone within which jet-like behavior prevails) of an ambient body of water receiving discharges of heated water. Such a model is needed for evaluation of thermal effects upon the natural environment, to develop techniques for the prevention of recirculation of heated discharges into cooling-water intakes, for improved design of laboratory scale models, and for insuring that discharge configurations meet legal temperature regulations.

MODEL/METHOD

The approach involves, first, a review of the available scientific literature in the areas of turbulent jets, stratified flows, and surface heat loss to provide guidelines and departure points for the development of basic governing equations. An extensive, detailed review of the best available analytical and experimental investigations of turbulent jets, flows with stable gradients, and heat transfer in turbulent fluids is presented. A tabular summary of previous theoretical investigations is presented to show the number of physical dimensions and the factors affecting temperature distribution considered by each.

The model developed is a three-dimensional turbulent jet simulation of a horizontal discharge of heated water at the surface of a large body of ambient water which is either stagnant or flowing. In the initial model development, theory is developed for predicting the three-dimensional velocity and temperature distribution within a discharge jet. The governing equations include basic equations for water flow in three dimensions, incorporating the Boussinesq approximation. Simplifications and assumptions required to develop a soluble set of equations are presented. A solution for a non-buoyant horizontal discharge is obtained by proposing similarity forms for velocity and temperature and by assuming linear jet spreading.

The case of a buoyant jet with no cross current is developed taking into account the structure of the jet, lateral momentum, and vertical entrainment. For ambient cross flows, the governing equations are the same as those for the buoyant jet with extra terms to account for jet curvature. Contingent upon an extensive set of assumptions, the integrated equations governing a deflected, buoyant jet are developed and summarized in a four-page table.

The solutions of all governing equations are performed using a fourth-order Runge-Kutta integration technique which is contained in the IBM FORTRAN Scientific Subroutine Package.

FACTORS INCLUDED

Turbulent jets, turbulent flows with density gradients, surface heat exchange, surface discharges of heated water, basic governing equations, nonbuoyant surface jets, buoyant jets, deflected jets, bottom slopes and jet separation from bottoms.

KEY ASSUMPTIONS

1) Turbulent Jet (basic)

(a) The discharge is three-dimensional, with unsheared critical core and turbulent region in which the velocity and temperature distributions are related to centerline values by similarity functions.

(b) Horizontal and vertical entrainment of ambient water into the jet is proportional to the jet centerline velocity.

(c) The vertical entrainment is a function of the local vertical stability of the jet.

(d) The buoyancy of the discharge increases lateral spreading.

2) Deflected and Buoyant Jets

(a) The deflection of the jet is sufficiently gradual that locally a cylindrical coordinate system may be defined in terms of the coordinate system moving with the jet and the fixed coordinate system.

(b) Cross flow velocity is small compared to the jet centerline velocities and distortion of the jet is small.

(c) The lateral spreading velocity is related to the difference in buoyant and nonbuoyant spreading.

(d) Other specific and detailed assumptions to permit application of the governing equations to each of four separate jet regions.

(e) A jet will not separate from the bottom, over the entire width of the jet, until the buoyant effects of lateral spreading cause the slope of the bottom of the jet to be less than the bottom slope.

(f) Until buoyant separation occurs, the buoyant terms of the model have no effect on the jet.

(g) Frictional effects are negligible and the longitudinal momentum equations are valid.

(h) Once separation occurs, losses in the entrained flow between the jet and the bottom are small.

KEY DATA REQUIRED

Initial temperature difference between discharge and ambient water, the discharge velocity, discharge channel geometry, surface heat transfer coefficients, ambient cross flow, and bottom slope.

RESULTS/COMMENT

A heated discharge is physically modeled in a laboratory basin. All of the important parameters, including the cross flow and bottom slope are varied and three dimensional temperatures are measured in a series of experimental heated discharges. The validity of the theoretical models is verified by comparisions of theoretical and experimental values.

The results of experiment and computations show that the rate of temperature decrease in the jet and the vertical and lateral spreading are controlled by the initial densimetric Froude number, the ratio of discharge channel depth to width, and the bottom slope. A cross flow is shown to deflect the jet, but does not greatly affect the temperature distribution. Surface loss does not significantly affect the temperature distribution in the heated discharge within the region treated by the theory.

The theoretical model predicts the limits of the near field temperature distribution in which temperature rises are significant. The diversion of natural flows by jet entrainment can also be observed by theoretical calculations.

The dependence of the maximum vertical discharge depth on the densimetric Froude number enables the design of a bimmer wall structure which requires knowledge of the depth of the heated layer at the intake. The calculated dimensions, temperature and position of the discharge jet aids in the location of an intake for prevention of recirculation as well as the evaluation of the success of discharge configurations in meeting temperature standards.

The authors conclude that satisfactory field application of the theory to prediction of temperature in an actual heated discharge is possible if temperatures, velocities and the geometry of the discharge can be schematized by means of steady state temperatures and velocities, and by an equivalent rectangular channel. However, if it is not clear whether the jet will entrain water from one or both sides, or if irregularly shaped solid boundaries (including bottom) will distort the jet from the form assumed in the theory, then meaningful schematization is not possible.

SIMILAR/RELATED REFERENCES

"Mathematical Models for the Production of Thermal Energy Changes in Impoundments" Water Resources Engineers, Inc., Walnut Creek, California, December, 1969.

"Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water," Tetra Tech, Inc., 630 N. Rosemead Blvd., Pasadena, California 91107, Oct., 1970

Water Resources Engineers, Inc., Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments. Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130 EXT, December, 1969.

DESCRIPTORS

OBJECTIVE

Purpose of this study was to devise a mathematical model which would represent the thermal changes which may be expected under alternative hydrologic, hydraulic and climatologic condition for operating reservoirs. This work is to supplement the model developed previously by Water Resources Engineers, Inc. in their investigation of the Columbia River System.

MODEL/METHOD

Two improvements of the original model were made:

a. A generalized empirical expression for the eddy conductivity coefficient was derived, and (b) the influence of reservoir stability on the vertical extension of the withdrawal zone for reservoir outlets and the zone influence for inflows was accounted for.

The resulting model accounts for external heat exchange by the usual budget components. Internal heat transfer is accomplished by the penetration of short-wave radiation, eddy diffusion, and vertical advection. The model also simulates weakly stratified reservoirs. These are represented as a set of smaller reservoirs coupled to each other by the heat and mass conservation requirement. Each small reservoir is described by the basic model, and the tilted isotherms are produced by connecting the temperature profiles at the longitudinal midpoints of the segments.

FACTORS INCLUDED

The basic hydrologic, meteorologic and hydraulic factors affecting reservoirs were considered.

KEY ASSUMPTIONS MADE

1. Weakly stratified reservoir is characterized by tilted isotherms along the longitudinal axis.

2. The eddy conductivity efficient is described by an empirical linear log-log relationship between the eddy conductivity coefficient and stabilities.

3. A uniform velocity distribution is assumed.

4. Energy input by the wind is an exponential function of depth.

5. The selective withdrawal feature of the model assumes that the reservoir outlets are slots which extend laterally across the face of the dam.

KEY DATE REQUIRED

1. Physical data: location, elevation, intake elevations, spillway, mean gaged inflow, mean ungaged inflow, average reservoir discharge to volume ratio.

2. Meteorological data: solar radiation, atmospheric radiation, cloud cover, barometric pressure, wind speed, air temperature (wet bulb and dry bulb), solar radiation extinction coefficient in evaporation coefficient.

RESULTS/COMMENTS

The model was tested and verified on Hungry Horse Reservoir for which the assumption of horizontal isotherms is valid. The primary difference between the model results and the observed behavior was that the model tends to enter the cooling cycle one to two weeks early. A test of the segmented model on Lake Roosevelt gave satisfactory results, although some difficulties were encountered in simulating the reservoir during the period of cooling in September.

The primary limitations of the model are: (a) it is one dimensional while the solution describes a three-dimensional body of water and (b) the selective withdrawal feature, as incorporated into the model, assumes that the reservoir outlets are slots which extend laterally across the face of the dam.

The functional form of the eddy conductivity coefficient must be used with caution until more experience is gained through the application of the model to additional reservoirs.

SECTION G

STUDIES AND MODELS OF ECONOMIC AND SOCIAL ASPECTS OF STREAM SYSTEMS AND WATER QUALITY - ABSTRACTED PAPERS

Author and Title	Page
1. Hall, W.A., Butcher, W.S. and Esogbue, A., "Optimization of the Operation of a Multiple Purpose Reservoir"	G-2
2. Hamilton, H.R., Goldstone, S.E., et alia, "A Dynamic Model of the Economy of the Susquehanna River Basin: Phase II "	G-5
3. Heaney, J.P., "Mathematical Programming Analysis of Regional Water-Resource Systems"	G-7
4. Males, R.M., W.E. Gates, and J.F., Walker, "A Dynamic Model of Water Quality Management Decision-Making "	G-10
5. Upton, C., "Optimal Taxing of Water Pollution"	G-13
6. Wipple, William, Jr., "The Economics of Water Quality,"	C-15
7. Kerri, K.D., "A Dynamic Model for Water Quality Control"	G-18

Hall, W.A., Butcher, W.S. and Esogbue, A., "Optimization of the Operation of a Multiple Purpose Reservoir", Water Resources Research, Vol. 4, No. 3. pp. 471-477, June 1968

DESCRIPTORS

OBJECTIVE

A technique of analysis is presented in this paper by which the dynamic operation policies for planning or operating a single multi-purpose reservoir stream system producing hydroelectric power and providing water can be optimized for the maximum return from "firm" (on-peak) water, "firm" (on-peak) power, dump (off-peak) water and dump (off-peak) power, while meeting complex constraints (such as mandatory flood control storage variable in time, fish, wildlife, and recreational releases, navigation, salinity control or water right minimum flows, etc., as well as evaporation losses and inter-basin diversions).

MODEL/METHOD

The technique can be used as the suboptimization portion of a multiple reservoir system optimization by linear programming (Parikh, 1966). The fourth decision variable, dump water, is determined by the other three decision variables mentioned above and the equation of continuity over time. The procedure provides for optimization of the individual stream system in response to a given set of predetermined time-varying prices and input flows (authors use the "critical period hydrology" concept in use in California)over the total planning horizon for the three decision variables. The predetermined prices need not be actual "contract" prices; they can be shadow prices generated during iteration of the linear multiple reservoir-optimization shceme.

The objective function for the single reservoir optimization is given by the sum of income returns from expected "sale" of firm and dump water and energy, for the price schedule given for each of the N time intervals. Using the standard recursive procedures of dynamic programming, a generalized equation is written successively for one remaining time period, two remaining time periods, etc. Only the volume of water released is carried over into the next time period, and the power and water decisions are inherently interrelated in the model. The constraints used in the dynamic program are:

1. The allowable releases for each month must be greater than or equal to the minimum release that will bring the reservoir to its maximum storage level for the next month, and these releases must be less than or equal to the maximum release that will bring the reservoir to its minimum storage level.

2. The minimum release is the greater of either the feasible release for that month or the mandatory release.

3. If the energy function is less than or equal to the capacity limit on peak energy, then all the energy that can be produced will be on-peak energy.

4. If the energy function is greater than the capacity limit on peak energy but less than or equal to the capacity limit on total energy; then there will be two energy values: peak and non-peak energy.

5. If the energy function is greater than the capacity on total energy, then the maximum possible peak energy is produced, and the excess energy is thereby non-peak, or dump, energy.

6. The maximum allowable storage in any time period may not exceed total storage less the flood control reservation for that time period.

KEY DATA REQUIRED

Inflows (monthly), storages (initial and end), releases (mandatory), prices (monthly for dump and firm energy, single value for water released), hours (on peak hours, total hours in each month).

RESULTS/COMMENTS

1. Against the additional returns from reduced end storage must be weighed the risk of failure to regain normal (initial) storage before the onset of a second critical period. This aspect cannot be covered directly in the analysis, yet end storage decisions are an integral part of an overall optimum operating policy.

2. A key advantage of this analysis is that it requires considerably less running time than the previously employed linear program addressing the same problem.

3. The treatment of water quality as a simple low flow augmentation "requirement" or constraint is somewhat simplistic, from the point of view of water quality management.

SIMILAR/RELATED REFERENCES

1. Hall, W.A., and D. T. Howell, The optimization of single-purpose reservoir design with the application of dynamic programming to synthetic hydrology samples, J. Hydrol., 1, 355-363, December, 1963.

2. Parikh, S.C. Linear dynamic decomposition programming of optimal long-range operation of a multiple multi-purpose reservoir system, Proc. Fourth Intern. Conf. Operation Res., Boston, Massachusetts, September, 1966.

Hamilton, H.R., Goldstone, S.E., et alia," A Dynamic Model of the Economy of the Susquehanna River Basin: Phase II Susquehanna River Basin Group", Battelle Memorial Institute, Columbus, Ohio, August, 1966.

DESCRIPTORS

OBJECTIVE

The report outlines progress toward the development of a dynamic, mathematical model of the economy of the Susquehanna River Basin. In its present stage of development the model has been used to make projections of the Basin's economy. These projections are reported with an analysis of water-resource development in the Basin.

MODEL/METHOD

The study is separated into two phases: Phase I investigated the feasibility of building a dynamic model and Phase II has been directed primarily toward analyzing and tying together factors judged to have significant impact on the growth of the economy of the Basin.

Two primary divisions are established. The first is the division of the Basin into economic subregions, and the second is the division of each of these subregions into subsectors of interrelated variables for each major factor; these are demography, employment, water, electric power. Each subregion has been described by a series of fitted equations that are divided into subsectors. In each subsector are equations that tie the subsector to other subsectors.

The complete dynamic model can and has been used to accomplish the following functions: (1) To make economic and water-use projections for the Basin. Projections, by subregions, of population, employment, wages, unemployment, water-consumption, pollution, and many other variables can be made. (2) To project electric power demand. (3) As a guide to point out major influences on the economic development of the Basin. (4) To test the economic impact of building various alternative systems of river works. (5) As a guide to facilities planning.

RESULTS/COMMENTS

1. The relationship of economic growth to water-resource development in the Basin has been described through equations fitted to the major economic variables.

2. A useful dynamic model of the economy of the Basin has been developed and adopted for computer simulation.

Two overall conclusions of interest are:

1. Water is not a constraint upon the growth of the economy of the Susquehanna River Basin.

2. In general the economy of the Basin will grow more slowly than the nation over the next 50 years.

The study does not address water quality problems or their economic effects on the Basin. Furthermore, it does not address past or predicted effects of extreme low flows.

Heaney, J.P., "Mathematical Programming Analysis of Regional Water-Resource Systems," Proceedings of the ARWA National Symposium on the Analysis of Water Resource Systems, July 1968.

DESCRIPTORS

OBJECTIVE

The objective of the analysis is to allocate water resources among regions within a water resource system so as to achieve the "best combination of use" giving consideration to both tangible and intangible beneficial uses.

MODEL/METHOD

A river system is subdivided into study areas of two categories (a) headwater (one which does not have another study area upstream) and (b) interior. The model employs the concept of economic demand and competition for water rather than absolute requirements. The "best combination of uses" is defined as that combination which maximizes regional net economic benefits (gross value-added) while supplying certain minimum flows for intangible beneficial uses (e.g., preserving stream quality, fish, wildlife, esthetic values, etc.). Maximization is achieved by linear programming format which decomposes the problem into individual study area optimization schemes based on the Dantzig and Wolfe decomposition principle.

Each of the study areas determines its optimal water allocation (depending on cost of water, supply available and total value-added differences for alternate uses) and the associated imputed value of water to the area (change in net benefit if water supply is altered by one unit), using a linear program. The regional optimization consists of giving each study area an estimated quantity and value of water supplied (zero value for the first iteration), based or which each study area is optimized. Under these conditions, each study area solution yields an imputed value of water for the area. The process is iterated until all imputed values for headwater areas are equal plus all imputed values for interior areas are equal and less than the headwater value (barring areas with an oversupply of water, where value is zero).

This point represents the regional optimum. Using this optimum, the imputed cost (benefits foregone) of the flows reserved for intangible beneficial uses can be computed.

The model has been applied to the Colorado Basin divided into 44 study areas, using published economic data.

ASSUMPTIONS MADE

1. Basic economic inputs can be estimated.
2. Value-added is linear with water quantity for each alternate water use.
3. Time variations in water supply can be ignored or averaged out for the purposes of economic analysis.
4. There is no interaction with groundwater supply.
5. Total gross value-added is an adequate indicator of regional economic benefits.

DATA REQUIRED

1. Regional and study area water supply constraints.
2. Value-added for each alternate use vs. water quantity for each study area.
3. Supply quantities necessary for intangible beneficial uses.

FACTORS INCLUDED

Supply available; competition among alternate uses and subregions; overall regional economic benefits; water supply restrictions for intangible beneficial uses.

RESULTS/COMMENTS

In examining possible system states with respect to the imputed resource valuation, it can be determined whether or not river basin planning yields major economic advantages. The model offers a quantitative technique for evaluating the sub-region interdependencies that are the prime concern of regional optimization. By recognizing the decomposable nature of the river basin planning problem, it is possible to evaluate large systems in a consistent manner and a computationally feasible manner.

Applications of the model to the Colorado Basin show that major economic misallocations result from current water appropriations and current cost/benefit justifications of Bureau of Reclamation irrigation projects.

SIMILAR/RELATED REFERENCES

1. Heaney, J.P., "Mathematical Programming Model for Long-Range River Basin Planning with Emphasis on the Colorado River Basin," Ph.D. Dissertation, Northwestern University, Evanston, ill., 215 pp., 1968.

2. Heaney, J.P., A. Charnes, R.S. Gemmell, and H.B. Gotaas, "Impact of Institutional Arrangements on the Available Alternative Developmental Paths for Water Allocation and Pollution Control in the Colorado River Basin," _Proc. Third American Water Resources Associaiton Conference_, San Francisco, California, 12 pp., 1967.

Males, R.M., W.E. Gates, and J.F. Walker, A Dynamic Model of Water Quality Management Decision-Making, Final Report, Engineering Science, Inc., May, 1970.

DESCRIPTORS

OBJECTIVE

The study investigates the regional board decision making process. The disciplines of behavioral science and systems analysis are used in combination to assess the California system of Regional Water Quality Control Boards. The overall objective is the derivation of broadly applicable techniques of water quality management. Specific objectives are:

1. Assessment of the formal and informal objectives and attitudes of groups and/or individuals identified as participating in the decision-making process.
2. Determinations of procedures by which decisions are achieved.
3. Determination and evaluation of the consequences of a postulated informal decision-making structure for water quality management.

MODEL/METHODS

Since broadly applicable techniques are sought, it is implicitly assumed that the California system of regional control boards is representative of regional boards in general.

The approach is termed "environmental systems dynamics". It involves simulation modeling of the behavior of the components of a regional decision-making system, including feedback loops operative among components. Model component structure and parameter are based on quantitative assessment of qualitative information gleaned from extensive interviews with persons intimately involved with water quality decisions. The model is brought to an empirical fit with observed behavior patterns of a prototype California Regional Board System by arbitrary adjustment of non-measurable parameter values.

FACTORS INCLUDED

Key factors included in the model development involve the structuring and assessment of:

1. The hierarchy of management organization.
2. Dynamic interactions of pertinent factors and personnel pertaining to decision making.
3. Relationships among relevant water interest (objective) groups.
4. Regional versus centralized management.
5. The decision making process.
6. Perceptions of water quality management functions.
7. Perceptions of goals, conflicts, identities, etc., for all interest groups.
8. Regional board meeting procedures.

DATA REQUIRED

Classes of data collected and/or estimated subjectively from interviews include:

1. Scales of public and interest-group attitudes.
2. Response functions.
3. Impact functions.
4. Measures of public awareness of pollution problems.
5. Flow charts of decision processes and procedures.

RESULTS/COMMENTS

Structuring and testing of the model and an example of use is described for the limited situation of two distinct interest groups (industrial and conservationist) interacting with an extended board. Five functional areas are structured: generation of pollution, desired quality of water based on uses, perceived quality of water based on pollution levels, negotiation of responses based on magnitude of the problem and time factors, and response. Within the situation content, the model is used to examine the sensitivity of the decision-making process to behavioral and technical parameters. Partial results of the case are presented as time simulations of actual pollution levels.

1. The structure and philosphy of the regional board relies heavily on the concept of assimilative capacity, i.e., the capacity of the environment to assimulate wastes.

2. System response to discharger behavior patterns is critical, i.e., the relative independence of the board with respect to waste dischargers determines the rate at which abatement is achieved.

The simulation model as structured in this paper is comprised of a series of basic block diagrams. The text infers the existence of a mathematical model fitted empirically to information given in case studies, but the mathematical model is never formally presented. A major difficulty in social system research, that of quantification of data, is acknowledged, but the specific relationships developed for use as hard data in the mathematical model are not presented. It is therefore difficult to judge the full validity of the conclusions and recommendations provided.

Upton, C., "Optimal Taxing of Water Pollution", Water Resources Research, Vol. 4, No. 5, October, 1968.

DESCRIPTORS

OBJECTIVE

This paper deals with the problem of achieving efficient water quality management through effluent taxes.

MODEL/METHOD

The model uses standard calculus methods to minimize cost of maintaining a specified water quality (DO level) by minimizing the sum of low flow augmentation costs (publicly funded) and amount of treatment expenditure for each polluting discharger (privately funded), where cost of augmentation is a fixed function of flow. Cost of augmentation is only assumed to be a convex increasing function of the amount of pollutant load removed.

It is shown that optimum taxes on pollution discharges can be set in such a way as to drive dischargers to the minimum total cost operating point, at least when the individual plant treatment cost functions are known. Using this framework two tax schemes which do not require knowledge of the treatment cost function on the part of the taxing authority are examined as to optimality.

The first one, the increased permissible waste load method, makes each firm's assessment proportional to its share of excess DO deficit contributed over and above the total DO deficit contribution that results in acceptable water quality standards without augmentation. This scheme is equivalent to the "required dilution water method" where tax is based on the amount of dilution water required to maintain stream quality. These taxes are optimal only if cost of augmentation is directly proportional to amount of augmentation flow. In the second scheme, the waste discharge method, the firm's assessment is proportional to its share of the total discharge.

This scheme is optimal only if cost of augmentation is directly proportional to total stream flow.

KEY ASSUMPTIONS

1. There is only one form of central treatment available:low flow augmentation.
2. The only alternative way for a firm to reduce pollution is to treat waste at the plant site after the pollutants are created in the production processes.
3. The marginal cost for both low flow augmentation and decentralized treatment is positive.
4. A one dimensional parameter,DO deficit,can describe total stream water quality; this parameter consists of a simple weighted sum of individual discharge loads (e.g., measured as BOD) divided by total stream flow. It is assumed that the weights used are constant and independent of stream flow (though this is not true even under linear rate DO stream models unless all discharges occur at a single stream location).
5. The level of output of each firm and the amount of pollutants produced by each firm's production process are fixed.

DATA REQUIRED

Waste load of each firm, downstream linearized effects of each discharge, cost vs. scale of low flow augmentation.

RESULTS/COMMENT

1. The cost of maintaining a minimum water quality standard is minimized when the marginal cost of treatment at each plant, weighted by the plant's marginal effect on the water quality, is set equal to the marginal cost of low flow augmentation.
2. Results demonstrate that the second taxation scheme is preferable to the first scheme if the cost of augmentation is continuous and concave upward (decreasing return to scale). No general results are available.

The unrealistic nature of strong assumptions such as 4. and 5. considerably restrict the applicability of this model.

Wipple, William, Jr., "The Economics of Water Quality," Water Resources Research Institute, Rutgers - The State University, New Brunswick, New Jersey. In: Proceedings of the First Annual Meeting of the American Water Resources Association, AWRA, Urbana, Illinois, 1965.

DESCRIPTORS

OBJECTIVE

This paper is an expository discussion of the economics of water quality intended to develop a rationale for an economic approach to quality control analysis. Water use concepts and principles of economic costs and benefits, including treatment of aesthetics, are discussed. It is concluded that it should be possible to make fair evaluations of all economic benefits that accrue as a result of improved water quality.

MODEL/METHOD

Supply-demand concepts developed in economics are considered for application to analysis of total usable streamflow, including return flows. The technique is rejected as insufficient to solve major problems.

The graphical procedure of indifference curves is introduced as applicable to the process of assessing alternatives for obtaining usable (within standards) water at downstream points. The indifference curve method is illustrated by an example involving graphic contours of all combinations of waste treatment reduction and low-flow augmentation capable of achieving a given stream quality level. Straight line contours representing equal cost combinations of the two alternatives are superimposed on the same graph; points of tangency between the equal cost and equal "quality" contours identify optimum combinations (in the sense of minimum cost for a given quality level). The example problem is constrained to analysis of a single pollutant.

A concept of "pollution sets" is explored. Pollution sets are defined as combinations of multiple pollutant concentrations in a stream. A set encompasses a range within which an optimum solution is likely to be found. Each pollution set thus represents a criterion range for BOD, heat, chemical wastes, etc. There exist corresponding costs for reducing pollution to the levels specified by a set, and corresponding economic losses caused by pollutants in the stream. For each set there also corresponds an optimum combination of effluent treatment, flow augmentation or alternate means of reducing pollution, and a corresponding lowest total cost of achieving the given degree of control of the various wastes embraced by the set. It is proposed that various sets can be compared using appropriate incremental costs, benefits, and quality criteria to arrive at an optimal result.

ASSUMPTIONS MADE

1. Each damage caused by waste can be identified and the costs of treatment can be associated directly with that damage to determine net benefit.

2. Treatment levels can be related to corresponding changes in receiving stream water quality.

3. Stream water quality is assumed to be uniform.

RESULTS/COMMENTS

The economic bases for effluent charges and subsidies are discussed by means of an example and graphic illustration involving an optimal solution for a single pollutant and three points of water use. The objective function is to minimize total costs by optimizing the costs of treating versus accepting pollutants discharged by the involved users. The problem is constrained to a single additive measure of pollution. Assumptions include:

1. The economic costs to downstream users of accepting residual wastes of upstream polluters are known.

2. Pollutant effects from upstream outfalls are directly additive at downstream points for purposes of estimating intake treatment requirements and costs.

It is concluded from the example that definite relationships can be determined between the costs of treating effluent wastes at various points and the economic costs occasioned by the residual wastes discharged. Using marginal and total costs calculated for the various users of the example, a philosophical discussion is presented concerning the economic implications of various approaches for imposing effluent charges in a basin system.

This paper provides graphic insight into the principles of economic benefit and cost/benefit/tradeoffs. However, practical application of the techniques presented is essentially negated by the highly multidimensional nature of real world problems compared to the simplification and approximations necessary to implement the proposed graphical techniques in a comprehensible format. Identical concepts have since been implemented in large scale mathematical programming models.

Kerri, K. D., "A Dynamic Model for Water Quality Control," Journal of the Water Pollution Control Federation, Vol. 39, No. 5, May, 1967, pp. 772-786.

DESCRIPTORS

OBJECTIVE

The qualitative structuring of an acceptable approach to an equitable system of effluent charges as an economic means of providing a monetary incentive for waste dischargers to reduce the quantity of waste in their effluents.

RESULTS/COMMENTS

The report is an expository discussion of a proposed method of handling effluent charges. A cooperative or association composed of waste dischargers is proposed. Waste treatment costs are reduced for an example of five industrial waste dischargers by merging their individual waste treatment resources into a single, controlled system in lieu of attempting to conform separately to an effluent standard. The water quality objective (e. g. a specified, in-stream DO concentration) is achieved through a pollution control system that is based on economic analysis.

Digital computer programs are necessary to compute the optimal economic solution, but the programs are identified by references to other research efforts and are not included in the discussions of this study.

In general terms, a minimum cost solution is obtained from a dissolved oxygen cost of treatment matrix solved by nonlinear programming techniques. This solution is inserted into a program that analyzes the influence of the major dischargers in a basin on the dissolved oxygen concentrations in receiving waters and the assimulative powers of numerous reaches of a main stream and its tributaries.

The association members pay the total cost (only institutional costs are included) estimated by the economic solution, the costs being distributed among the discharger members in proportion to the quantity of waste generated by each member. A key feature of the proposed association is the implementation of a pivotal waste treatment facility. The pivotal facility may be any member of the association selected (and if necessary upgraded) to meet specified characteristics concerning size, location with respect to critical reaches, and flexibility with respect to marginal costs of treatment over a broad range of treatment requirements.

Based on the degree of treatment (indicated for each member) to achieve a basic quality condition of the entire receiving stream by reaches, the nonpivotal facilities maintain relatively constant rates of waste removal regardless of the condition of the receiving stream. The pivotal facility (by its design) is able to vary the amount of wastes it removes over a considerable range. The pivotal facility, thus, acts to reduce its level of treatment (and hence costs) during periods when water quality is far above standard, and increases the level of treatment during adverse conditions. By careful design of the entire system, utilization of the pivotal facility concept leads to considerable reduction of association total costs.

Bases for eligibility in the association are proposed. Possibilities include legal requirements for all basin dischargers to join, pressure tactics based on unreasonable effluent discharge requirements to force membership, or the simple option of joining the association as opposed to otherwise conforming to the regulatory agency established standards. The last option is recommended.

Relationships between the association and the responsible, basin, regulatory agency are examined. Cooperation and coordination between the association and the agency are deemed essential.

The problems of compensation to individual association members for their existing facilities are analyzed and arrangements for equitable settlements are proposed.

Rigorous economic analysis of existing facilities and of required new construction is essential. The operating strategy for the association system must be developed, using high speed computers and systems analysis techniques, to specify the removal of wastes from a critical reach (or reaches) at minimum cost. An approximating graphical approach to the analytic procedure is illustrated.

Dynamic conditions that will confront an association are addressed. The increased costs (to the association) from increased volumes of wastes to be treated as basin industrial activity increases (outside the association) are concluded to be a reasonable exchange for the privilege of using all of the available assimilative capacity of the receiving stream. Conditions for the acceptance of new, participating or nonparticipating association members, and special considerations for expansion of production processes at existing sites (both association and nonassociation) are addressed. If changes in water quality standards occur, it is concluded that advantages accrue to the association because of system flexibility permitting selective upgrading of parts (only) of the system -- costs being distributed throughout the system. Problems of jurisdictional boundaries and association mergers are evaluated, and the handling of costs sustained by the association when a member chooses to leave the group are analyzed.

Cost savings is the major advantage observed in the proposed association concept. At one extreme (all basin waste dischargers included), the association concept would approach that of a basin authority; at the other extreme (a multiplicity of associations), it would approach the zoning concept proposed by other authors.

SECTION H

DATA COLLECTION TECHNICAL DATA AND COST DATA FOR SYSTEMS ANALYSES OF WATER QUALITY - ABSTRACTED PAPERS

Author and Title	Page
1. Gannon, J.J. and C.T. Wezernak, "Collection and Interpretation of Stream Water Quality Data,"	H-2
2. Kalinske, A.A., "Economics of Aeration in Waste Treatment,"	H-4
3. McKeown, James J., "Studies on In-Stream Aeration,"	H-5
4. Meyer, C.F., "Using Experimental Models to Guide Data Gathering,"	H-6
5. Stone, Ralph and C. Schmidt, "A Survey of Industrial Waste Treatment Costs and Charges,"	H-8
6. Warner, D.L., "Deep Wells for Industrial Waste Injection in the United States: Summary of Data,"	H-10

Gannon, J.J. and C.T. Wezernak, "Collection and Interpretation of Stream Water Quality Data," Third American Water Resources Conference, AWRA, San Francisco, November, 1967.

DESCRIPTORS

OBJECTIVE

In this paper the steps involved in designing and executing practical stream surveys are described.

MODEL/METHOD

The steps include:

1. Continuous physical measurements of the river flow at a number of key locations.

2. Preparation of hydrographs consisting of a graph of the daily average flow with respect to time, relating water quality data to flow conditions during the sampling period. This includes high or low runoff, ascension and recession hydrograph curves and normal flows.

3. Knowledge of discharge rates from all the known pollution points including waste treatment plants, storm and sanitary sewers and drainage ditches, etc.

4. Accurate time of travel or velocity record along the stream. The authors use a Rhodamine B dye as an external tracer in conjunction with a fluorometer operating either in a boat for times through an impoundment, or at bridges for times in free flowing river sections for measuring the time of travel.

5. Collection of water quality samples and testing including measurements of the coliforms, dissolved oxygen and BOD.

6. Exploration of existing information on water quality from sources such as water treatment plants, sewage treatment plants, private industries, and governmental agencies at the State and Federal level.

7. Measurement of thermal stratification with associated influence on water quality (e.g., where a river flows through an impoundment).

8. Summarization and interpretation of the collected information. A number of suggestions have been given by the authors.

RESULTS/COMMENTS

A case study of a survey of the Clinton River is described. The survey investigated research on abnormal river BOD reductions and arrived at significant conclusions regarding the influence of such factors as photosynthesis on dissolved oxygen level by means of carefully controlled day and night sampling.

Kalinske, A.A., "Economics of Aeration in Waste Treatment," Eimco Corporation, Salt Lake City, Utah. In: Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

The paper is confined to discussions of the efficiency and power consumption of the three aeration methods for those aerobic processes where the organisms are kept in suspension in liquid waste--primarily the activated sludge process.

RESULTS/COMMENTS

The three principal oxygenation methods presently in use in liquid waste treatment are discussed, i.e., these are diffusion of compressed air, air diffusion with submerged turbine dispensers, and mechanical surface entrainment aerators. Methods for calculating power requirements and oxygen absorbed are presented and discussed. Factors pertinent to the assessment of true cost are identified for each oxygenation method. Three principal methods for evaluating the performance of aerators either under test conditions or in the field under actual operating conditions and the implications of aerator performance on cost are discussed. It is concluded that diffusion methods require double the power of mechanical surface aerators for large-scale installations. Capital and operating costs are not given.

McKeown, James J., "Studies on In-Stream Aeration," Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968

DESCRIPTORS

OBJECTIVE

The paper presents a discussion of field measurements of dissolved oxygen and estimates of oxygen transfer capabilities of dams and short sections of turbulence in streams due to rapid loss of elevation. The use of mechanical aeration for the purpose of increasing the DO content at critical oxygen sections of streams is also evaluated.

RESULTS/COMMENTS

Previous work involving analysis of data collected above and below numerous weirs and cascades is summarized. Existing, validated models for calculating deficit rates of dissolved oxygen as a function of pollution levels, height of fall, and water temperature are summarized.

Useful, new data are presented on dissolved oxygen determinations from dam and spillway investigations. Data on the transfer efficiency of mechanical, surface aerators is developed and presented. DO profiles resulting from various location configurations and numbers of aerators are presented. Operational scheduling patterns (i.e. on-off periods), water recycling patterns, and special horizontal flow or circulation enhancers are examined as methods of optimizing DO profiles in shallow waters.

Although no models have been developed in this paper, the data presented are useful as input for studies to improve mechanical aeration coefficients for inclusion of in-stream aeration as pollution abatement alternatives in basin planning and stream modeling.

Meyer, C.F., "Using Experimental Models to Guide Data Gathering," Journal of the Hydraulics Division, ASCE, 1970.

DESCRIPTORS

OBJECTIVE

The use of a series of analytical models is examined as a possible minimal-cost approach to guiding data-gathering programs while simultaneously developing a plausible model to be used for predicting the consequences of management decisions.

MODEL/METHOD

The technique employed is an empirical sensitivity analysis of the parameters defining the mathematical model; the example used is a groundwater basin model with 144 nodes, 482 parameters defining the mathematical record. A number of ways of systematically varying the model parameters are examined:

1. Simple multiplication of each parameter set (e.g., all storage coefficients)by a factor.

2. Application of statistical perturbations to each parameter set using random number generation.

In either case, a small number of runs (not full Monte Carlo procedure) of the entire model with perturbed values proportional to the estimated measurement error for each parameter set are executed; the results are displayed to give time records or map displays of the difference between the base case solution and the perturbed solution (e.g., in terms of piezometric heada for the groundwater model). Data-gathering effort is then allocated proportionally to the sensitivity in model output observed for each parameter set.

RESULTS/COMMENT

It is concluded that straight multiplication of an entire parameter set by a single factor introduce skew into the results which produces an illogical representation of basin groundwater. Statistical measures such as normal, lognormal, and triangular distributions can eliminate or minimize skewed results.

The extremes of Gaussian distributions can lead to unlikely or impossible negative results in groundwater studies. The lognormal distribution overcomes the problem of negative values, but extreme values continue to pose difficulties.

Triangular and log-triangular probability distributions covering the range of estimated measurement error are suggested as the most suitable methods for perturbing groundwater system parameters for sensitivity studies, the latter being suitable where error is measured in percentages.

Time saving techniques utilizing direct computer print out of key sensitivity summaries and displays in a suitable format for easy data comparison and analysis are proposed.

Stone, Ralph and C. Schmidt, "A Survey of Industrial Waste Treatment Costs and Charges," Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968.

DESCRIPTORS

OBJECTIVE

The paper gives data on the types and extent of sewerage/treatment charges imposed by United States cities (based on mailed questionnaire) plus data on national industrial waste volumes and strengths.

RESULTS/COMMENTS

Through a questionnaire circulated among sewering agencies it was found that about 33% of responding cities provide separate waste charges while the remaining two-thirds make no distinction between residential, commercial and industrial sewerage service. Most of those providing separate rate schedules used volume or sewer size as the basis for charges. About 5% of the agencies billed the industry on the basis of the amount of BOD and suspended solids in addition to basic volume charges. The sample results indicate that collection and treatment costs generally decrease as served population increases; the average cost per citizen in a community of under 100,000 inhabitants is approximately $20.00 per month, and it falls to $14.00 per month in larger cities.

The sewerage charge ordinances of four cities were applied to nine hypothetical firms with equal volume and same BOD component. It was found that charge variations were as high as 100 fold. The interesting thing was the relationship between the degree of pollution and cost in the case of one city; for a waste volume of 0.5 mgd containing an average BOD of 2000 mg/lbs. the sewer charge was $3,500.00 per month where as with other cities the charge for same amount of BOD was as little as $30.00 per month. It follows that in many cases heavy sewer users get a "free ride" with the additional cost of treating their waste being absorbed by the public and other industries through taxation.

The following types of sewer service charges were found:

1. Fixed, uniform charges per sewer connection.
2. Charge per plumbing fixture.
3. Fixed percentage of waste bill.
4. Sliding scale of water consumption.

5. Size of sewer connection.
6. Size of water meter.
7. Corporate revenue taxes.
8. Volume of sewage.
9. 1 through 8 with separate rate schedules by type of industry.
10. Volume plus surcharge for BOD suspended solids, grease, or other special waste constituents.

Analysis shows that the most equitable arrangement is generally that whereby a part of the revenue is obtained by charges based on BOD, suspended solids, and volume of waste discharge to the sewer and another portion by property taxes on all properties.

Warner, D.L., "Deep Wells for Industrial Waste Injection in the United States: Summary of Data," Federal Water Pollution Control Administration, Water Pollution Control Research Series Publication No. WD-20-10, Cincinnati, Ohio, November, 1967.

DESCRIPTORS

OBJECTIVE

The paper is confined to a summary of the available current information regarding the location, design, and operating experience of existing industrial waste injection deep wells; an important waste disposal technique for concentrated, relatively untreatable wastes.

RESULTS/COMMENT

Data on one hundred and ten industrial waste injection wells located in 16 states are summarized. Information on distribution of injection wells by geography and type of industry plus rate of increase is developed. Statistics such as distribution of well depths, type of rock used for injection, rates of waste injection, pressure at which waste is injected are also developed. Cost data are not presented.

SIMILAR/RELATED REFERENCES

Manning, J.C., "Deep Well Injection of Industrial Wastes", Hydro-Development, Inc., Bakersfield, California. In: Proceedings of the 23rd Industrial Waste Conference, Purdue University, Lafayette, Indiana, 1968.

SECTION I

COMPUTER PROGRAMS FOR BASIN AND STREAM WATER QUALITY/HYDROLOGICAL MODELS - ABSTRACTED PROGRAMS

Program Title	Page
1. A BRANCH-AND-BOUND ALGORITHM FOR MINIMIZING COSTS OF WASTE TREATMENT	I-2
2. DYNAMIC PROGRAM FOR OPTIMIZATION OF WATER QUANTITY AND QUALITY IN STREAM BASINS	I-4
3. LOW FLOW AUGMENTATION MODEL FOR MAINTAINING DISSOLVED OXYGEN	I-5
4. RIVER BASIN SIMULATION PROGRAM	I-6
5. WATERSHED HYDROLOGY SIMULATION MODEL	I-8

COMPUTER PROGRAM

A BRANCH-AND-BOUND ALGORITHM FOR MINIMIZING COSTS OF WASTE TREATMENT

DESCRIPTORS

PURPOSE OF COMPUTATION

A modified Geoffrion algorithm is used to solve the integer programming formulation of the problem of finding the minimum regional cost of wastewater treatment to meet DO stream standards using zoned treatment requirements.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
IBM 7094

TYPICAL RUNNING TIME
1. A problem with 8 categories, 10 treatment levels, and only 4 quality constraints, ran in about 6 minutes.

2. A problem which was modeled with Delaware Estuary data, contained 7 categories, 13 treatment levels, and 15 constraints. Running time was about 27 minutes.

INPUT REQUIREMENTS

Reach dimensions, influence coefficients for each reach, costs by treatment levels, discharger categories.

OUTPUTS

Outputs are tabular in format and include optimal levels of treatment and cost by category (or zone), minimum total costs for basin, and the dual solution.

AVAILABILITY

The model and method are described in: Liebman, J.C., "A Branch-and-Bound Algorithm for Minimizing the Costs of Waste Treatment, Subject to Equity Constraints", Proceedings of IBM Scientific Computing Symposium on Water and Air Resource Management, October, 1967

Documentation and source decks are available on request from:

Dr. J.C. Liebman
John Hopkins University
Baltimore, Maryland

COMPUTER PROGRAM

DYNAMIC PROGRAM FOR OPTIMIZATION OF WATER QUANTITY AND QUALITY IN STREAM BASINS

DESCRIPTORS

PURPOSE OF COMPUTATION

Program will compute optimal costs of water quantity and quality for multi-stage river basins involving complex combinations of treatment costs and waste return flows.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
IBM 360/65 adaptable to wide variety of computer types.

TYPICAL RUNNING TIME
The IBM 360/65 can perform cost optimization calculations for basin system comprised of several reaches with a waste outfall in each reach in approximately 45 seconds.

INPUT REQUIREMENTS

Tabular inputs for physical and biological state variables as well as costs. Three dimensional table look-up and interpolation routines are required.

OUTPUTS

Tables of individual stage returns, combined stage returns, and optimal management policies with minimum annual costs.

AVAILABILITY

Complete description of model is available in report by L.W. Meier, Jr. and C.S. Shih, Application of Specialized Optimization Techniques in Water Quantity and Quality Management with Respect to Planning for the Trinity River Basin, Final Report, Water Resources Institute, Texas, 1970. (Computer program in research code only, i.e., not developed for general use. Plan to develop and document complete program for field use and general availability in near future).

COMPUTER PROGRAM

LOW FLOW AUGMENTATION MODEL FOR MAINTAINING DISSOLVED OXYGEN

DESCRIPTORS

PURPOSE OF COMPUTATION

A model is presented for use in predicting the dissolved oxygen distribution in a river basin for discrete waste sources. When flow augmentation is available the model can be used to compute the additional flow required to maintain dissolved oxygen at a given level.

LANGUAGE
FORTRAN

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Key input data include point discharge loadings of BOD, initial values for DO, deoxygenation rates as a function of reach, relationship between discharge, river velocity and sources of flow augmentation.

OUTPUTS

Outputs include dissolved oxygen profiles by reaches in a river basin and specification of amounts of flow augmentation needed to maintain specified DO levels.

AVAILABILITY

Details of the mathematical model are described in A Systems Analysis Method for Water Quality Management by Flow Augmentation by J.L. Worley, Environmental Protection Agency, Water Quality Office, Region X, Portland, Oregon.

COMPUTER PROGRAM

RIVER BASIN SIMULATION PROGRAM

DESCRIPTORS

PURPOSE OF COMPUTATION

Provides Monte Carlo simulation of the monthly hydrology, flow routing and mixing of a river system with tributaries, reservoirs and waste discharges (up to 15 reaches, 10 confluence points, 10 discharges, 15 reservoirs, one degradable pollutant and 4 conservative pollutants). The program can simulate the in-stream effects of time-varying flows, discharges, withdrawals, pollutant loads and reservoir release schedules as well as compute quantity and quality deficiencies.

LANGUAGE
FORTRAN IV

MACHINE COMPATABILITY
IBM 360/65

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

a. System geometry-locations and distances of confluence points, gaging stations, reaches, discharge points and reservoirs

b. Fixed hydrological inputs-flow and runoff statistical parameters, fixed withdrawals, fixed flow and quality requirements, reservoir capacities, minimum pool storage, starting storage, reservoir losses, reoxygenation/deoxygenation parameters, etc.

c. Variable system design choices-reservoir operating policy rules, discharge pollutant loads, variable withdrawals, variable flow and quality requirements.

OUTPUTS

Outputs consist of hydrographs and stream quality records for any of 50 gaging stations as well as deficiencies in flow or quality wher compared with pre-set requirements. Additional outputs include reservoir storage/release records.

AVAILABILITY

Complete program description is available in a report titled River Basin Simulation Program, W.C. Pisano FWPCA, August, 1968, distributed on request through the Environmental Protection Agency, Washington, D.C.

COMPUTER PROGRAM

WATERSHED HYDROLOGY SIMULATION MODEL

DESCRIPTORS

PURPOSE OF COMPUTATION

Flood routing program for square-shaped watershed elements chosen small enough so that hydrologic properties are uniform over element. Program combines elements to form total watershed. Events related to runoff included through flood routing procedures to produce composite result for the entire watershed. Use is constrained to small watersheds.

LANGUAGE
FORTRAN

MACHINE COMPATIBILITY
Adaptable to wide variety of computer types.

TYPICAL RUNNING TIMES
Indicated in report referenced below.

INPUT REQUIREMENTS
Include basic hydrologic data, e.g. water infiltration rates, rainfall rates, etc... plus physical/topographic characteristics for each watershed element.

OUTPUTS

Runoff hydrograph as function of spatial differences over the watershed. Hydrograph printout as watershed contours in process of development.

AVAILABILITY

Complete details of the computer program are included in report by L.F. Huggins and E.F. Monk, The Mathematical Simulation of the Hydrology of Small Watersheds, Technical Report No. 1, Water Resources Research Institutes, Purdue University, Lafayette, Indiana.

(Note: Preceding source now out of print, but copies available through Department of Interior, Office of Water Resources Research, Washington, D.C.)

SECTION J

COMPUTER PROGRAMS FOR TREATMENT PROCESS AND PLANT ANALYSIS/DESIGN - ABSTRACTED PROGRAMS

	Program Title	Page
1.	A COMPUTER ALGORITHM FOR SOLVING THE POSYNOMIAL GEOMETRIC PROGRAMMING PROBLEM	J-2
2.	COMPLETE DOMESTIC WASTE TREATMENT SYSTEM DESIGN CC071	J-4
3.	COST ESTIMATING COMPUTER PROGRAM FOR WASTEWATER TREATMENT PLANTS	J-5
4.	ENVIROTECH MUNICIPAL EQUIPMENT PROGRAM	J-6
5.	EXECUTIVE PROGRAM FOR PRELIMINARY DESIGN OF WASTEWATER TREATMENT SYSTEMS	J-7
6.	A GENERALIZED COMPUTER MODEL FOR STEADY-STATE PERFORMANCE OF THE ACTIVATED SLUDGE PROCESS (CSSAS)	J-9
7.	MATHEMATICAL MODEL FOR COMPLETE SECONDARY TREATMENT SYSTEM	J-11
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COMPUTER PROGRAM

A COMPUTER ALGORITHM FOR SOLVING THE POSYNOMIAL GEOMETRIC PROGRAMMING PROBLEM

DESCRIPTORS

PURPOSE OF COMPUTATION

Solves the posynomial geometric programming problem. The program includes a main program which acts as an executive controller. Several subroutines participate in the mechanics of the geometric programming solution. Program includes an accuracy control feature with automatic recycling of subroutines until the optimum weights found meet the requirement of the control.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
IBM 360/65

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Inputs include variables and constants associated with the objective function and the constraints. The matrix of exponents of the posynomial variables is read along with cost coefficients, controls concerning accuracy of solution, and starting values for the primal problem variables.

OUTPUTS

Output includes printed solutions for both the primal and the dual programs.

AVAILABILITY

The computer program is described briefly in "Geometric Programming: New Optimization Techniques for Water Resource Analysts" by W.L. Meier, R.W. Lawless, and C.S. Beightler, Texas A&M University, College Station, Texas, Proceedings of the Fourth American

Water Resources Conference, AWRA, Urbana, Illinois, 1968. (Computer program currently in research code only and not available for general use).

COMPUTER PROGRAM

COMPLETE DOMESTIC WASTE TREATMENT SYSTEM DESIGN CC071

DESCRIPTORS

PURPOSE OF COMPUTATION

This design and costing program uses Dorr-Oliver design concepts and equipment sixing relationships for three separate process systems: ABC systems for complete mixed activated sludge, PEP system for phosphorus removal, and Farrar plus FS disposal for sludge dewatering and incineration.

LANGUAGE

N/A

MACHINE COMPATIBILITY

N/A

TYPICAL RUNNING TIME

N/A

INPUT REQUIREMENTS

Key inputs include flow, specific pollutant concentrations of the influent stream and effluent requirements.

OUTPUTS

The program sizes all equipment and structures to meet given performance requirements. It computes the volume of all side streams, the consumption of electrical power and chemicals, and equipment cost estimates which can be provided separately.

AVAILABILITY

The program is available only at Dorr-Oliver, Inc. Computations using the program are made at no charge to the customer by Dorr-Oliver. Inquries should be directed to Dorr-Oliver, Inc., 77 Havemyer Lane, Stanford, Connecticut 06904, Environmental Equipment and Systems Division, Attention: Marketing Department.

COMPUTER PROGRAM

COST ESTIMATING COMPUTER PROGRAM FOR WASTEWATER TREATMENT PLANTS

DESCRIPTORS

PURPOSE OF COMPUTATION

The program estimates capital, amortization, operations and maintenance, and total treatment costs for standard wastewater treatment plants. Cost calculations are based on standard design parameters. Rule of thumb relationships are used to size equipment, structures and internal streams.

LANGUAGE
FORTRAN

MACHINE COMPATIBILITY
IBM 1130/8K

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Inputs include design parameters, amortization factors, construction cost index, and hourly wage rates.

OUTPUTS
Total and component cost breakouts, size and capacity estimates, operating costs.

AVAILABILITY

Computer program documentation and source deck available (no cost) through R.C. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio, 45226.

COMPUTER PROGRAM

ENVIROTECH MUNICIPAL EQUIPMENT PROGRAM

DESCRIPTORS

PURPOSE OF COMPUTATION

The program is designed to provide the consulting engineer with a complete equipment analysis of a sewage plant system comprised of primary and secondary treatment processes to meet fixed performance specifications. The speed of the program permits modification of input data for the development and examination of alternative results.

LANGUAGE
N/A

MACHINE CAPABILITY
Suitable for terminal system; computer type/model not indicated.

TYPICAL TUNNING TIME
Typical running time indicated as "minutes".

INPUT REQUIREMENTS

Program input requires at least influent flow, BOD load and removal required, but can use up to 1000 variables related to engineering and cost functions.

OUTPUTS

Output includes equipment sizing, capital costs, operating costs and engineering component data for the complete primary-secondary treatment system.

AVAILABILITY

The program is available as a terminal computer system installed in customer's office for a monthly fee. Inquiries should be directed to Mr. Robert Sherwood, Municipal Equipment Division, Envirotech Corporation, 100 Valley Drive, Brisbane, California 94005.

COMPUTER PROGRAM

EXECUTIVE PROGRAM FOR PRELIMINARY DESIGN OF WASTEWATER TREATMENT SYSTEMS

DESCRIPTORS

PURPOSE OF COMPUTATION

Computes quasi-steady-state performance and cost of groups of conventional and advanced wastewater treatment processes arranged in any configuration. The program contains a main program and twelve process subroutines. Each subroutine computes the performance and cost of a single wastewater treatment process based on empirical relationships. Additional subroutines are developed and can be used to total costs for the various processes in a variety of cost categorizations and to print all pertinent data relative to each process in a specific format.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
IBM 1130/8K

INPUT REQUIREMENTS

Inputs include influent stream flows and specific pollutant concentrations, effluent load requirements, the tolerable error when recycle streams are invloved, cost coefficients and process decision variables.

OUTPUTS

Output is printed in the following sequence:
a. Description of system simulated.
b. Volume, flow and concentrations of 15 contaminants in each stream number.
c. Names of all processes involved with pertinent data including capital costs for each process; operating cost, amortization cost, and total treatment cost.
d. General cost items including capital cost index, amortization factor, cost of engineering, con-

tractor profit, contingencies and omissions, and land.

e. Total costs including total capital cost, total amortization cost, total operating and maintenance cost, and total treatment cost for the system.

AVAILABILITY

Description of model contained in Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems, No. WP-20-14, U.S. Department of the Interior, Federal Water Quality Administration, Advanced Waste Treatment Branch, Division of Research, Cincinnati, Ohio, November 1970.

(Report and source deck available at no charge through R.C. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226).

COMPUTER PROGRAM

A GENERALIZED COMPUTER MODEL FOR STEADY-STATE PERFORMANCE OF THE ACTIVATED SLUDGE PROCESS (CSSAS)

DESCRIPTORS

PURPOSE OF COMPUTATION

The CSSAS Program has been developed to aid in understanding the relationships which govern the quasi-steady-state performance of the activated sludge process. The model can be arranged to simulate conventional, modified, extended aeration, or contact stabilization. It provides for simulation of all known aspects of the process though several important questions relating to design and operation of the process remain unresolved. The model has been partly validated using data ranging from the short detention time, low mixed liquor suspended solids "modified process" to the extended aeration process.

LANGUAGE
FORTRAN

MACHINE CAPABILITY
IBM 1130/8K

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

For both heterotroph and nitrosomona bacteria, growth equation parameters are required as well as total aerator volume, the number of equal volume sub-aerators, the compaction ratio for the final settler, and a number of stream characteristics such as volume flow, concentration of particulate and dissolved 5-day BOD, concentration of non-biodegradable volatile suspended solids, etc.

OUTPUTS

A large number of output variables are available including volatile suspended solids, total BOD out, waste stream flow, active solids, concentrations of various solids etc.

AVAILABILITY

Complete description of model contained in A *Generalized Computer Model for Steady State Performance of the Relivated Sludge Process*, R. Smith and R.C. Eilers, U.S. Department of the Interios, Federal Water Quality Administration, Advanced Waste Treatment Branch, Division of Research, Cincinnati, Ohio, October 1969. Report and source deck available at no charge through R.C. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.

COMPUTER PROGRAM

MATHEMATICAL MODEL FOR COMPLETE SECONDARY TREATMENT SYSTEM

DESCRIPTORS

PURPOSE OF COMPUTATION

A computational program to handle the significant preliminary design cost and performance relationships for conventional municipal treatment systems including primary settling, activated sludge, sludge thickening, anaerobic digestion of primary and waste activated sludge, sludge elutriation, vacuum filtration of sludge, sludge incineration, and sludge drying beds. The program represents an attempt to provide a program capable of calculating the performance and cost of treatment systems as a whole, based on empirical relationships which have been developed for the processes individually. The model computes performance and cost as a function of the characteristics of the feed streams as well as the operating and design decisions associated with each process. The program is in a developmental state and remains to be fully validated through precise data from full-scale plant operations.

LANGUAGE
FORTRAN IV

MACHINE CAPABILITY
IBM 1130/8K

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Key inputs include a quantitative description of the influent raw sewage stream in terms of volume, temperature, specific pollutant loads, etc. Decision parameters which specify the mode of operation or the design criteria for each individual process are also required.

OUTPUTS

Include construction costs; operating and maintenance cost, cost of consumable items such as chemicals and power, and total costs for each process and for the entire system.

AVAILABILITY

The details of the mathematical model are included in Preliminary Design and Simulation of Conventional Wastewater Renovation Systems Using the Digital Computer, Report No. WP-20-9, U.S Department of the Interior, Federal Water Quality Administration, Advanced Waste Treatment Branch, Division of Research, Cincinnati, Ohio, March 1969. Technical Report and source deck available at no charge through R.C. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.)

COMPUTER PROGRAM

MATHEMATICAL MODEL FOR TERTIARY TREATMENT BY LIME ADDITION

DESCRIPTORS

PURPOSE OF COMPUTATION

A cost-estimating routine for the lime clarification process used downstream from an activated sludge secondary treatment process. The program computes the size of process equipment, the amount of chemicals, electrical power, operating and maintenance labor, capital and installation costs, and operating and maintenance costs.

LANGUAGE
FORTRAN

MACHINE CAPABILITY
IBM 1130/8K

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Quality variables and flows for the secondary treatment effluent; required quality of the tertiary treatment effluent.

OUTPUTS

Cost breakouts for tertiary treatment equipment, supplies power and operating costs.

AVAILABILITY

Details of the mathematical model are contained in Robert R. Taft Water Research Center Report No. TWRC-14; source deck available at no cost through R.C. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.

COMPUTER PROGRAM

MATHEMATICAL MODEL FOR A TRICKLING FILTER

DESCRIPTORS

PURPOSE OF COMPUTATION

A mathematical model of the trickling filter-final settling process based on empirical relationships is used to compute the relationship of the various physical properties of the trickling filter and the final settler necessary for least cost preliminary design based on desired BOD removals. The model also includes capital, operating, and maintenance costs.

LANGUAGE
FORTRAN

MACHINE COMPATIBILITY
IBM 360/65

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Inputs include a large number of parameters related to waste characteristics, physical properties of the trickling filter, effluent requirements, and a variety of cost factors.

OUTPUTS

Outputs include component sizing estimates, characteristics of internal streams, BOD removals, and total cost plus cost breakdowns.

AVAILABILITY

A description of the model is contained in A Mathematical Model for a Trickling Filter, by J.F. Roesler and R. Smith, U.S. Department of the Interior, Federal Water Quality Office, Advanced Waste Treatment Research Laboratory, Robert A. Taft Water Research Center, Cincinnati, Ohio, February 1969.

(Report and source deck available at no charge through Mr. Joesph Roesler, Advance Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.)

COMPUTER PROGRAM

A MATHEMATICAL MODEL FOR A WASTE STABILIZATION POND

DESCRIPTORS

PURPOSE OF COMPUTATION

The model provides estimates of preliminary design and cost data for aerobic waste stabilization ponds to meet specified capacity and removal efficiency; the model is based on empirically fitted process relationships.

LANGUAGE
FORTRAN

MACHINE CAPABILITY
IBM 1130/8K

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Major input parameters are temperature, dissolved oxygen levels, sunlight radiation, gains and losses due to rain and evaporation, desired BOD removal and influent flows with specific pollutant loads.

OUTPUTS

In addition to sizing estimates for components, the program also computes capital, operating, and maintenance costs.

AVAILABILITY

The details of the program are included in a report which is available at no charge through Mr. Joseph Roesler, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.

COMPUTER PROGRAM
TIME-DEPENDENT COMPUTER MODEL FOR THE ACTIVATED SLUDGE PROCESS

DESCRIPTORS

COMPUTES WHAT

This digital computer program consists of a numerical integration with respect to time of the rate of synthesis and mass balance equations for each of the aeration sub-volumes and for the process as a whole. The kinetic behavior of three classes of microorganisms is considered; these classes are: heterotrophs which convert biodegradable carbon to new cells, Nitrosomanas which converts ammonia to new cells and nitrite, and Nitrobacter which converts nitrite to new cells and nitrate. This model has been used to investigate a number of schemes for automatic control of the activated sludge process.

LANGUAGE

Fortran IV.

COMPATIBLE WITH WHAT MACHINES?

IBM 1130/8K

TYPICAL RUNNING TIME

Considering a 15-day simulation with only the time increment calculations from the 14th to the 15th day printed out with the time increment (H) = .01 of a day, it will take about ten minutes of IBM 1130 execution time to run this simulation.

SPECIAL INPUT REQUIREMENTS

Large masses of data are required for input. A step method was used to simulate the time dependent data that was gathered at the Hyperion plant in Los Angeles. The volume flow at the first station, the concentration of substrate at the first station mg/l and the final settler compaction ratio were used by the program as a step input from 100 values supplied for each by means of matrix input.

SPECIAL OUTPUTS

The program has provisions for printing process variables at each time point and electromechanical plotting.

AVAILABILITY

Report by Robert Smith and Richard G. Eilers entitled, "Simulation of the Time-Dependent Performance of the Activated Sludge Process Using the Digital Computer" available with source deck at no cost. Direct inquiries: Mr. R. G. Eilers, Advanced Waste Treatment Research Laboratory, 4676 Columbia Parkway, Cincinnati, Ohio 45226.

SECTION K

COMPUTER PROGRAMS FOR THERMAL POLLUTION MODELING - ABSTRACTED PROGRAMS

Program Title Page

1. MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM UTD K-2
2. MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM JTD K-3
3. MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISBRITUTIONS - PROGRAM SBJ2 K-4
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5. A MATHEMATICAL MODEL FOR PREDICTING TEMPERATURES IN RIVERS AND RIVER-RUN RESERVOIRS K-6
6. THEORETICAL CALCULATIONS OF HEATED DISCHARGE BEHAVIOR K-8

COMPUTER PROGRAM

MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM UTD

DESCRIPTORS

PURPOSE OF COMPUTATION

Solves for the distribution of excess temperature due to the effects of ambient turbulence, current, and surface heat exchange. Specifically, the program treats the case where the discharge, the ambient uniform current, and the surface heat exchange coefficient are time varying. The Crank-Nicolson method was employed in solving this problem numerically.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Program control number, time steps, sizes and time mesh schemes, characteristic velocity (u), at specified time points, kinetic surface heat exchange coefficient (K_e) and source strength (F_{co}) values, dimensionless dissipation parameter, source thickness, characteristic velocity, four y coordinates and two coefficients for defining vertical diffusion coefficient profiles, values of u, K_e, and F_{co} at specified time; spacing in x for each printout variable.

OUTPUTS

Two decay coefficients, time profiles for major input and output variables, zero-order moment of concentration, plume width characteristic, maximum value of concentration.

AVAILABILITY

Report and program are included in Koh, R.C.U., and Fan, L., Mathematical models for the prediction of temperature distributions resulting from the discharge of heated water into large bodies of water. Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130DW01/70, October, 1970.

COMPUTER PROGRAM

MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM JTD

DESCRIPTORS

PURPOSE OF COMPUTATION

Solves for the distribution of excess temperature due to the effects of ambient turbulence, current, and surface heat exchange. Specifically, the program treates the case of a steady release into a steady undirectional shear current (current varies with depth but not with time). This program is based on Crank-Nicolson method.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Program control number, mesh and step sizes, dimensionless dissipation parameter, source level, source thickness, characteristic velocity, two y coordinates defining velocity in the x direction profile, four coordinates and two coefficients for defining vertical diffusion coefficient profiles, kinematic heat exchange coefficient, decay coefficient.

OUTPUTS

Space profiles of major input and output variables, zero-order moment of concentration, plume width characteristic, and maximum value of concentration.

AVAILABILITY

Report and program are included at: Koh, R.C.Y., and Fan, L., Mathematical models for the prediction of temperature distributions resulting from the discharge of heated water into large bodies of water. Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130DW010/70, Oct., 1970.

COMPUTER PROGRAM

MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM SBJ2

DESCRIPTORS

PURPOSE OF COMPUTATION

Solves for the dispersion of heat resulting from the horizontal discharge of a two-dimensional warm jet at the surface into a quiescent, cooler ambient. The effects of source momentum, source buoyancy, entrainment, surface heat exchange, and interfacial shear are all included in the computation.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Entrainment coefficient, dimensionless surface heat exchange coefficient, densimetric Froude number, inverse of Reynolds number, integration limits, two control variables for step size.

OUTPUTS

Dimensionless distance, dimensionless density deficiency, dimensionless thickness, local densimetric Froude number, layer thickness after jump, Froude number after jump.

AVAILABILITY

Report and program are included at: Koh, R.C.Y., and Fan, L., Mathematical models for the prediction of temperature distributions resulting from the discharge of heated water into large bodies of water. Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130DW010/70, Oct., 1970.

COMPUTER PROGRAM

MATHEMATICAL MODELS FOR THE PREDICTION OF TEMPERATURE DISTRIBUTIONS - PROGRAM RBJ

DESCRIPTORS

PURPOSE OF COMPUTATION

Solves for the distribution of excess temperature resulting from the subsurface discharge of warm cooling water from power plants into an ambient fluid which may be stratified in arbitrary manner. The numerical integration used for the solution of this problem utilizes a fourth order Runge-Kutta scheme.

LANGUAGE
FORTRAN IV

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Jet velocity, jet diameter, jet temperature, jet density, jet discharge angle, jet discharge depth, jet spacing, entrainment coefficient for round jet or for slot jet, density and temperature depth profiles in the ambient in tabular form,

OUTPUTS

Space profiles of jet width, dilution, jet temperature, jet density, ambient density, ambient temperature, and temperature excess.

AVAILABILITY

Report and program are included at: Koh, R.C.Y., and Fan, L., Mathematical models for the prediciton of temperature distributions resulting from the discharge of heated water into large bodies of water. Environmental Protection Agency, Water Quality Office, Water Pollution Control Research Series 16130DW010/70, October, 1970.

COMPUTER PROGRAM

A MATHEMATICAL MODEL FOR PREDICTING TEMPERATURES IN RIVERS AND RIVER-RUN RESERVOIRS

DESCRIPTORS

PURPOSE OF COMPUTATION

A steady-state, one-dimensional model is solved primarily for use in predicting temperatures in rivers which are regulated by dams with run-of-the-river (or small usable storage capacity) reservoirs. The model may also be used in systems having reaches which are free-flowing. The method considers finite volumes of water, or water parcels, which are released from an upstream starting point at specified intervals of time. Individual parcels are followed downstream through open river reaches and reservoirs, and a history of temperature changes is computed. The program includes one main program and nine subroutines

LANGUAGE
The model is coded in FORTRAN H.

MACHINE COMPATIBILITY
N/A

TYPICAL RUNNING TIME
N/A

INPUT REQUIREMENTS

Key input data includes river cross-sectional characteristics, meteorological/runoff data, water surface elevation data, evaporation and sensible heat data.

OUTPUTS

Output is given by parcel number and reach location. Results are in terms of changes in parcel temperature due to weather, flow regulation, and advected sources.

AVAILABILITY

The mathematical model is described in detail in A Mathematical Model for Predicting Temperature in Rivers and River Run Reservoirs by John R. Yearsley, Working

Paper No. 65, United States Department of the Interior, Federal Water Pollution Control Administration, Northwest Region, Protland, Oregon, March 1969.

(The program deck can be obtained from the EPA Northwest Regional Office, Portland, Oregon)

COMPUTER PROGRAM

THEORETICAL CALCULATIONS OF HEATED DISCHARGE BEHAVIOR

DESCRIPTORS

PURPOSE OF COMPUTATION

The program solves an analytic model predicting the temperature distributions in the near field of an ambient body of water which result from discharges of heated water. The discharge is assumed horizontal from a rectangular open channel at the surface of a large receiving body of water which may have a bottom slope or crop flow at right angles to the discharge. The theoretical model development (which has been validated by a series of laboratory experiments)assumes a three dimensional turbulent jet discharge with unsheared initial core and a turbulent region in which velocity and temperature distributions are related to centerline values by similarity functions.

The computer program consists of a main program and subroutines. The main program sets up the initial conditions for each calculation and calls the appropriate subroutines. Computation is in terms of velocity and temperature fields comprising the near field of the heated jet for a series of time steps.

LANGUAGE
FORTRAN IV, G level, Mod 3.

MACHINE COMPATIBILITY
IBM 360/65

TYPICAL RUNNING TIMES
N/A

INPUT REQUIREMENTS

Inputs include an indicator for number of calculations and sets of the following parameters for each calculations: initial densimetric Froude number, bottom slope, channel aspect ratios, surface heat loss coefficient initial angle of the discharge, flow, temperature and dimensions of the discharge channel and receiving stream, initial values for jet dimensions, maximum allowable numerical truncation error for each dependent variable at each time step, and spreading rate of the turbulent regions of a nonbuoyant jet.

OUTPUTS

Outputs are printed in terms of sets of independent variables and nondimensional parameters relative to velocities, temperatures, and jet boundary dimensions, jet core region dimensions, the spread rate of the jet and the location of the jet in terms of a fixed coordinate system. Jet dilution and heat flow are also computed and printed.

AVAILABILITY

Complete details of the mathematical model and a summary of the computer program are included in *An Analytical and Experimental Investigation of Surface Discharges of Heated Water*, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, February, 1971 [For further information concerning availability of source deck contact author K.D. Stolsenbach or D.R.F. Harleman, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology, Cambridge, Mass., 02139].

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